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Dynamic Properties of the International Space Station throughout the Assembly Process

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ABSTRACT

Attitude control and spacecraft dynamics have always demanded serious attention from spaceflight personnel. Proper utilization of the basic tools of dynamics and controls can help alleviate the problems associated with the somewhat unpredictable nature of attitude control in the most basic spacecraft. Soon a new spacecraft will be placed in orbit that will truly test man, machine and the forces that bind them. The International Space Station is the culmination of works from 15 nations. It will orbit the Earth 200 miles high and will signal a new era in manned spaceflight and international cooperation. This platform of science will not miraculously appear overnight. Five years of on-location construction, requiring over 45 launches, will finally place the million-pound station in orbit. The dilemma is that each pound will transform the previous stage into an entirely new spacecraft, one with its own dynamics and means for control. This paper will describe this 5-year ordeal and monitor the stability of every configuration of the ISS while it's under the influence of Earth's gravity. Of 112 separate configurations, the ISS can only be confirmed stable throughout only 24. The remaining configurations are unstable about one, some or all of its body axes. Rendezvous maneuvers complicate matters, as the U.S. Space Shuttle has serious effects on the completed Station's dynamics, making it unstable about roll, pitch and yaw. Location of the principal axes in relation to body coordinates varies greatly and causes the station to rotate about its intermediate axis. In addition, dynamic analysis for a single construction phase is explained, calculated and compared to actual mass properties provided to NASA by Lockheed Martin's Systems Engineering Modeling and Design Analysis Laboratory with an error of less than one percent.

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INTRODUCTION

Space has always been a field for international competition. Ever since the space race of the 1950's and 60's, having the ability to send men and machines beyond the Earth's surface has been the trademark action for showing off your nation's technical expertise. The Space Race also provided a world audience for political statements. A new era is in the horizon for space exploration, and will be reached when two American astronauts fasten an American piece of space hardware onto an already orbiting Russian satellite, marking the beginning of the International Space Station's assembly sequence.

It is the largest international scientific and technological endeavor ever undertaken. It will be a permanent orbiting laboratory capable of performing long-duration research. According to NASA goals, it will:

- Expand U.S. leadership of the global community
- Forge new partnerships with other nations for the benefit of mankind
- Serve as a driving force for emerging technologies
- Inspire our children and encourage education
- Foster the next generation of scientists, engineering, and entrepreneurs,
- Satisfy humanity's need to explore

Construction will last over five years. When completed, the 950,000-pound station will span 356 feet across and be over 290 feet long. Orbiting at 220 miles and inclined at 51.6 degrees to the equator, it can be reached by all international partners involved. The U.S. has the responsibility for developing and ultimately operating major elements and system aboard the station. The elements include three nodes, a laboratory module, truss segments, four solar arrays, a habitation module, three pressurized mating adapters, a cupola, an non-pressurized logistics carrier and a centrifuge module. Canada is providing a 55-foot long robotic arm to be used for assembly and maintenance purposes. The European Space Agency is building a pressurized laboratory and logistics transport vehicle. Japan is building a laboratory with an attached exposed facility and logistics support vehicles. Russia is providing research modules, a service module with its own life support and habitation system, a science power platform that supplies about 20 kilowatts of electrical power, and Soyuz spacecraft for crew return and transfer.. Compared to individual undertakings by these countries, the ISS seems daunting indeed.

Table 1: Past, Present, and Future Space Station Comparison

Parameter	Skylab (1974)	Space Shuttle with Spacelab Module	Mir (in early 1996 with all modules)	International Space Station at assembly complete
Total Pressurized Volume (m3)	354	166	410	1,120
Total Modules	2	2	9	17
Total Mass (kg)	90,000	123,700	140,000	419,000
Number of Docking Sites	1	1	4	6
Number of Launches to Assemble	1	N/A	6	45
Total Power (kW)	18	7.7	<25	110
User Power (kW)	3	3.5 - 7.7	4.5	~50
Solar Array Area (m2)	165	0	430	~3,000
Data Rate (down in Mbps)	<1	45	7	50
Steady State Acceleration Near Center of Mass (in g x10-6)	(never recorded)	1-10	50-250	1 (requirement)

Its obvious that the International Space Station dwarfs all other previous attempts at long-duration space research. Its key attributes are the large supply of useable power, internal volume, and well-maintained microgravity. Each of these characteristics brings with them monumental challenges. Part of the challenge of the space station is that it represents many things to many people. Medical researchers see a platform perfect for crystalline growth. Some see a place where people of many different cultures can work together. Still others see a testing facility for future technology. But the designers and engineers of the ISS see an entirely different station, one that is most challenging to human exploration. They see a structure of immense proportions--a veritable monster of dynamics--which changes shape and disposition nearly every day. For them, ISS construction will be their finest hour over the forces of physics and kinematics. The ISS will take over 45 flights to complete, and with each flight, a new station is produced—one with its own shape, orientation, and stability parameters. Shuttle, Soyuz and Progress vehicles-rendezvous further complicate the problem.

This paper will describe the assembly sequence, show the various configurations for study, describe the analysis required, describe stability criteria and analyze ISS stability over the 5-year construction process.

BACKGROUND

The International Space Station Program has three distinct phases. Each phase builds on the accomplishments of the prior one, provides further capabilities, and represents new milestones in manned flight.

Phase One, now underway for the past two years, includes stays by U.S. astronauts on the Russian Mir Space Station, and dockings between Mir and the Space Shuttle. Phase One provides experience and test data used to improve ISS development, assembly, and operation. Information gained by this collaboration of NASA and RSA (Russian Space Agency) assets include technology demonstrations, risk mitigation, operational experience, and early science opportunities. The accomplishments of Phase One will undoubtedly bring new insight into ISS construction, repair, and management to increase ISS lifetime and ensure personnel productivity. When the Shuttle-Mir program ends in May 1998, U.S. astronauts will have had a continuous presence on Mir for almost 27 months.

Phase Two of the construction process begins with the launch of the Russian-built FGB, or Functional Cargo Block (most fitting translation) atop a Russian Proton rocket in June of 1998. Phase Two creates an orbital research facility that greatly expands the scientific and research activities begun in Phase One. This facility forms the core of the International Space Station. The United States and its international partners are currently designing and fabricating Phase Two elements, while crews for Phase Two Shuttle flights have already been selected and are in training. Russian hardware provides nominal power, propulsion, and attitude control during early operations. U.S. hardware will then add data management capabilities and increased electrical power, while guidance and navigation functions will be transitions from the Russian systems. Phase 2 develops the infrastructure and capabilities to provide permanent human presence and support early science and microgravity missions.

ISS construction is completed during the last phase, Phase 3. At this point, the Station is ready to support permanent human presence during its operational lifetime of at least 10 years. Phase 3 begins with U.S. Orbiter STS-102 and includes assembly of the Japanese Experiment Module (JEM), the Columbus Orbital Facility (ESA), two Italian-built nodes, and concludes with the delivery of the U.S. Habitation Module in December of 2003. Phase 3 also completes the truss as well as supplying the Station with additional U.S. power and research modules, and additional Russian science modules.

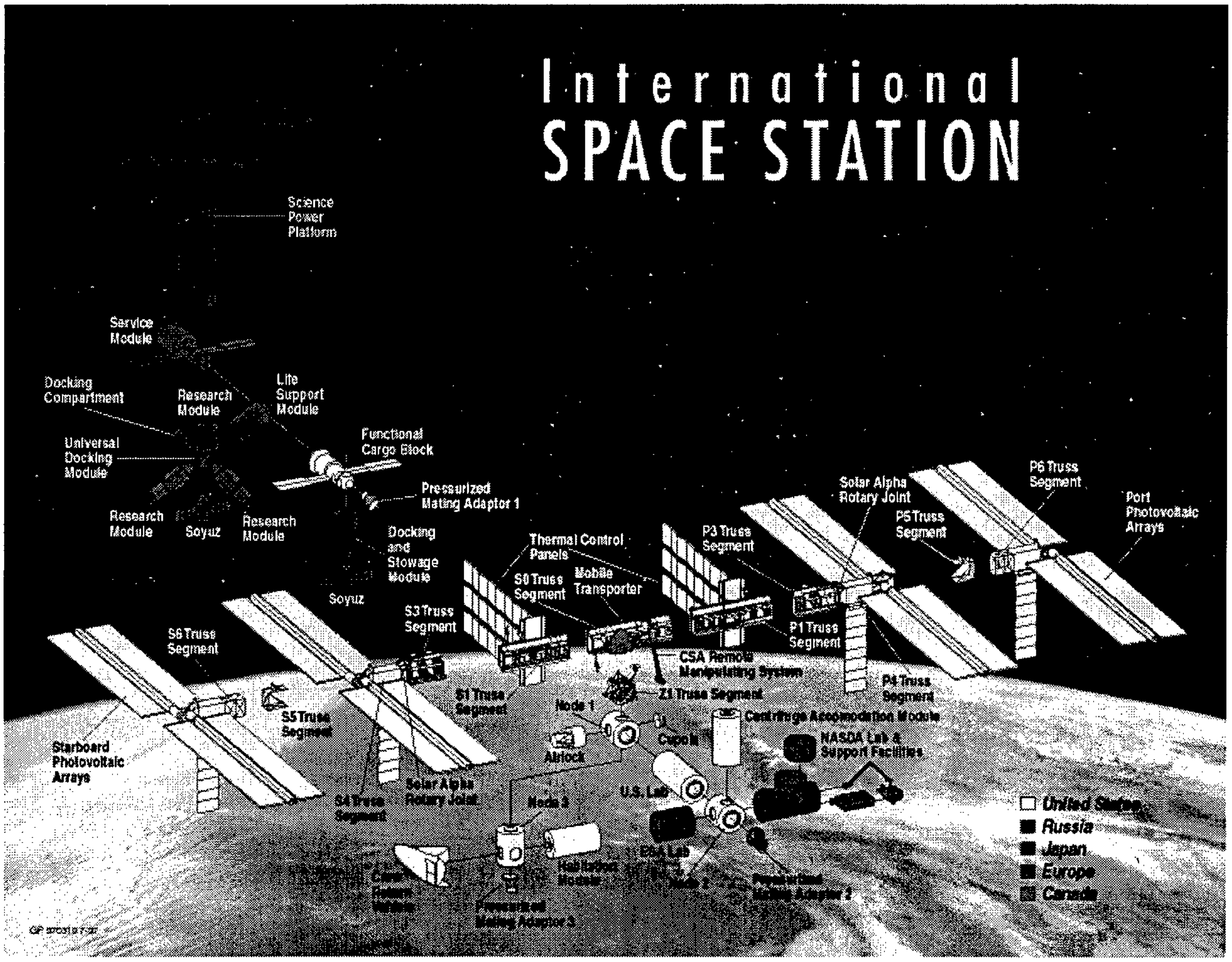


Figure 1: ISS Parts and Partners

PHASE ONE ACCOMPLISHMENTS

In February 1995, Commander Jim Weatherbee flew STS-63, a rendezvous and close-approach mission to the Mir space station. Vladimir Titov flew aboard the Shuttle, only the second Russian cosmonaut to do so. Though barely reported by the media, this mission marked the first of many challenging tests for human space flight and its larger dream, the International Space Station.

In March of 1995, NASA astronaut Dr. Norman Thagard spent 115 days aboard the Mir station with two cosmonaut hosts, Vladimir Dezhurov and Gennadiy Strekalov. To get there, Thagard became the first NASA astronaut aboard a foreign launch vehicle--a Russian Soyuz from Baikonur, Kazakstan. On June 1, 1995, the Russian Spektr module docked with Mir carrying 1000 kg of U.S. scientific hardware.

The first successful Mir-Shuttle docking occurred within the month by Captain "Hoot" Gibson in STS-71. The Shuttle Atlantis replaced the entire crew with two new cosmonauts and returned to Earth five days later. Colonel Ken Camoron commanded STS-74, the second Shuttle/Mir docking mission in November 1995. It delivered the new Docking Module, to be used in future Shuttle/Mir missions through 1998. This docking port was quickly exercised in March 1996 by Col. Kevin Chilton's STS-76, which transported astronaut Shannon Lucid. She remained until STS-79, to be replaced by John Blaha. Jerry Linenger on STS-81 subsequently replaced Blaha in January 1997.

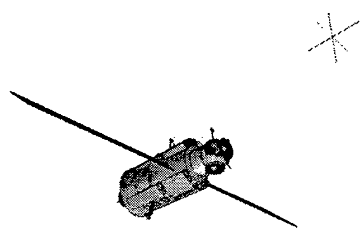
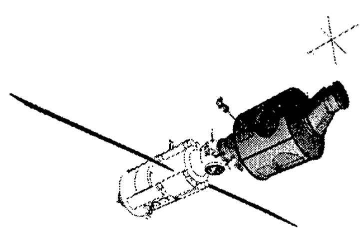
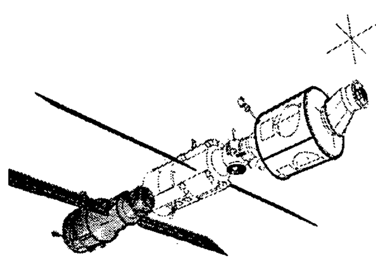
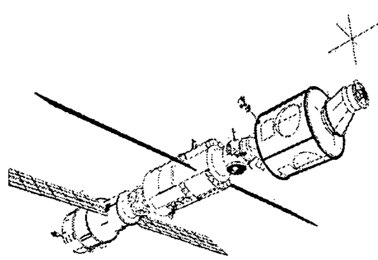
This joint program provided NASA with the opportunity to obtain much needed experience in a microgravity environment for durations far beyond the capability of the Shuttle. Over 140 experiments were conducted in areas of plant growth, life sciences, and microgravity science. But more importantly, Mir-Shuttle operations presented scenarios (that will be present during ISS construction) which could only be obtained in space--rendezvous, dockings, crew rotations, re-supply, and contingency operations. The people, problems, and perseverance of Phase One have unnoticeably set the stage for much publicized Phase Two of ISS assembly.

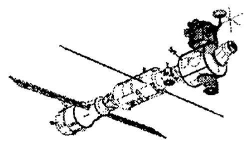
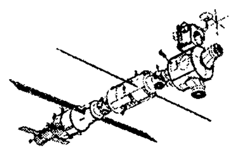
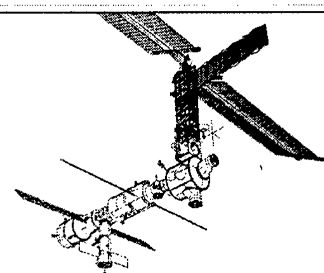
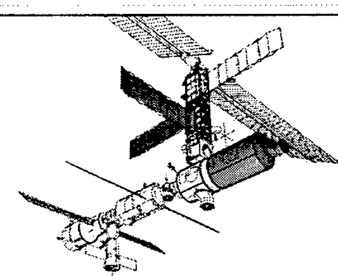
THE ASSEMBLY SEQUENCE

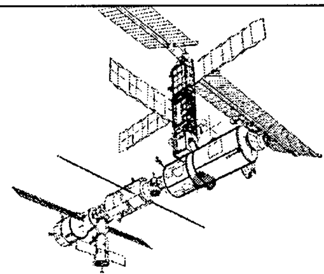
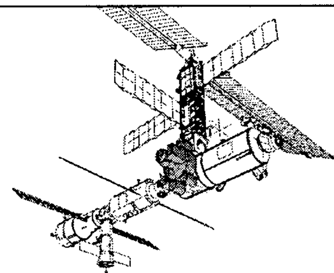
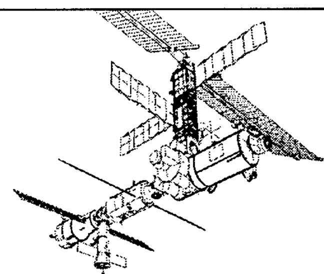
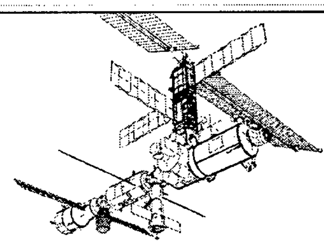
Senior government officials from 15 countries met in Washington on January 29, 1998 to sign agreements establishing a framework for cooperation on the design and operation of the International Space Station. The 1998 Intergovernmental Agreement on Space Station Cooperation was signed by Acting Secretary of State Strobe Talbott, as well as his counterparts from Russia, Japan, Canada and participating countries of the European Space Agency (Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland and the United Kingdom). NASA Administrator Daniel S. Goldin and his counterparts from the RSA, ESA, CANADA and Japan also signed memoranda of understanding to clarify more technical issues.

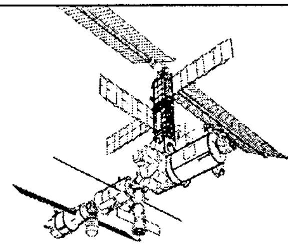
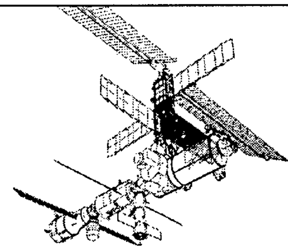
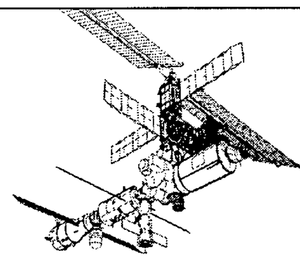
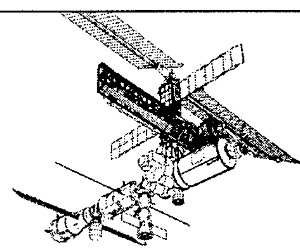
This political appearance solidified the essence of cooperation, but the design and assembly sequence of the station has never enjoyed such solidity. The design and sequence of assembly has undergone many changes from its initial conceptualization. Since the need for analysis and construction requires years of lead-time, finalizing a construction sequence has always been a top priority for NASA officials. The participating countries finalized the latest design sequence, called Revision C, in October of 1997 in Houston, Texas. It outlines the assembly of more than 100 components in low Earth orbit over the next 5 years. Revision C also describes in detail the component launch, rendezvous, and re-supply throughout the 5-year process. The following table is a guide to the 45 major flights of the sequence, including dates, components, launch vehicles, and illustrations for each free-flying configuration.

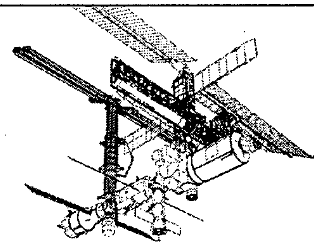
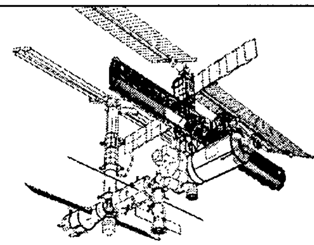
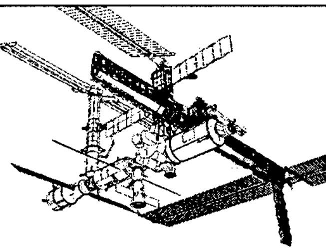
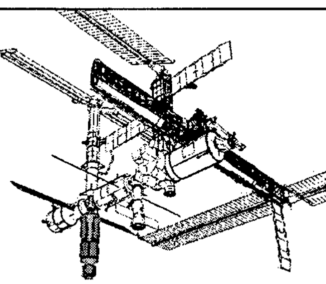
Table 2 : ISS Assembly Sequence, Revision C

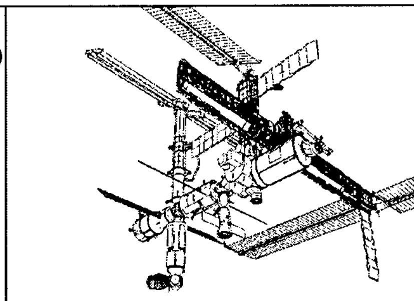
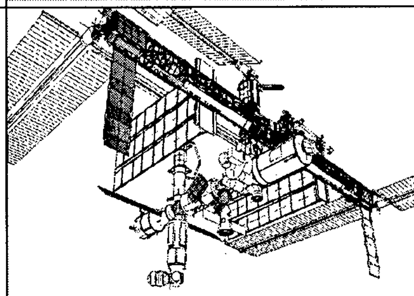
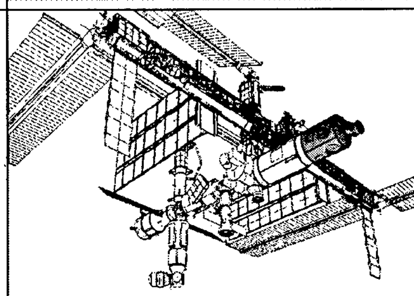
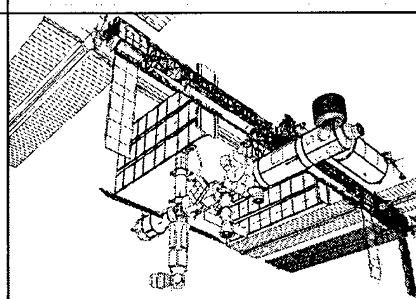
Launch Date	Stage	Launch Vehicle	Element Manifest	Configuration	Rationale/Comments
30 Jun 1998	1 A/R	Russian Proton	• Functional Cargo Block (FGB)		• FGB is a self-supporting active vehicle. • It provides propulsive control capability and power through the early assembly stages. • It provides fuel storage capability • It provides rendezvous and docking capability to the Service Module
09 Jul 1998	2A	U.S. Orbiter (STS-88)	• Node 1 • Pressurized Mating Adapters -1 & -2		• PMA-1 provides the interfaces between US and Russian elements. PMA-2 provides a shuttle docking location. • Eventually, Node 1's six ports will provide connecting points for the Z1 truss; U.S. lab; airlock; cupola; Node 3; and the early MPLM as well as the FGB.
01 Dec 1998	1R	Russian	• Service Module (SM)		• Primary Russian element; provides Environmental Control & Life Support System (ECLSS) functions to all elements. • Primary docking for Progress-type re-supply vehicles • Provides propulsive attitude control and re-boost capability
12 Dec 1998	2A.1	U.S. Orbiter (STS-96)	• Spacehab Double Cargo Module		• Logistics and resupply cargo

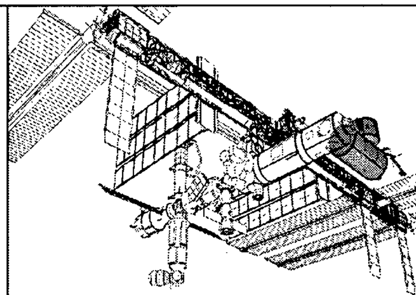
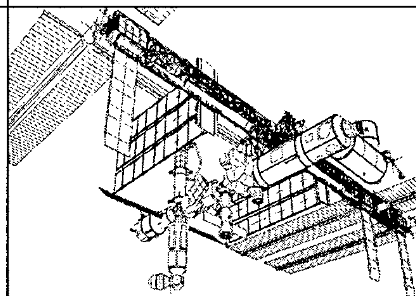
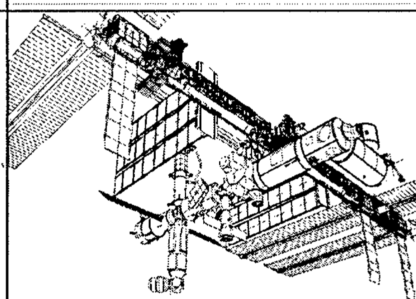
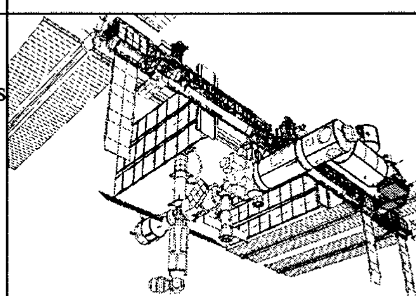
01 Jan 1999	3A	U.S. Orbiter (STS-92)	• Integrated Truss Structure (ITS) Z1 • PMA-3 • Ku-band • Control Moment Gyros (CMGs)		• ITS Z1 allows the temporary installation of the P6 Photovoltaic (PV) module to Node 1 (zenith) for early U.S. based power. • Ku-band communication system supports early science capability on 6A. • CMGs (aft) provide non-propulsive attitude control when activated on 5A. • PMA-3 provides a Shuttle docking for the P6 PV Module on 4A and Lab installation on flight 5A.
26 Jan 1999	2R	Russian	• Soyuz		• Established first station manning with three-person crew. • Provides assured crew return capability without the Orbiter present.
08 Apr 1999	4A	U.S. Orbiter (STS-97)	• ITS P6 • PV array • 4 battery sets • S-band transponders		• Establishes initial U.S Module-based power capability. • Installed in a temporary location on top of the Z1 Truss until Flight 1J/A when it's permanently attached to the P5 Truss. • Includes 2 PV Thermal Control System (TCS) radiators for early active thermal control. Also, the S-band communications system is activated.
20 May 1999	5A	U.S. Orbiter (STS-98)	• U.S. Lab		• Installed on Node 1 forward, provides initial U.S. user capability • Launched with 5 system racks pre-integrated • CMGs are activated

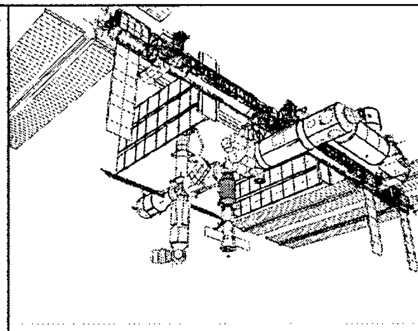
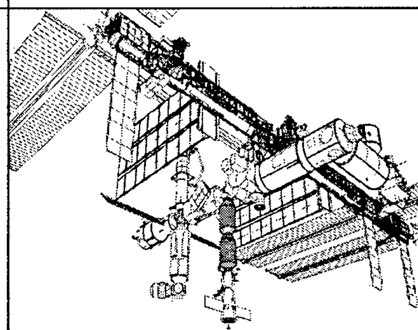
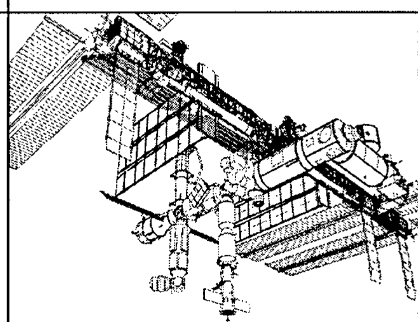
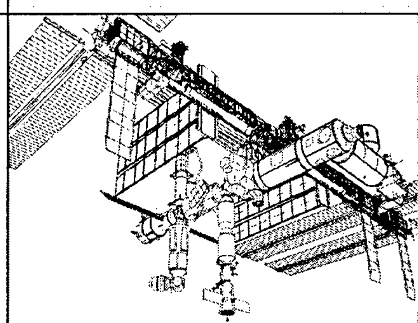
30 May 1999	6A	U.S. Orbiter (STS-99)	• MPLM (Lab outfitting flight) • Ultra High Frequency (UHF) antenna • Space Station Remote Manipulating System (SSRMS)		• Adds U.S. Lab outfitting with 6 system racks, 1 storage rack. • UHF antenna provide space-to-space communications capability for U.S. based EVA. • Delivers Canadian SSRMS needed to perform assembly operations on later flights.
12 Aug 1999	7A	U.S. Orbiter (STS-100)	• Joint Airlock • High Pressure Gas Assembly		• Airlock is attached to Node 1 (starboard); provides Station-based EVA capability for U.S. and Russian suits. • High pressure gas assembly augments the Service Module gas re-supply system.
PHASE TWO COMPLETE: INTIAL SCIENCE CAPABILITY					
04 Nov 1999	7A.1	U.S. Orbiter (STS-102)	• MPLM (Mini Pressurized Logistics Module)		• U.S. stowage racks, ISPRs. • Two additional battery sets are delivered and installed on the P6 PV Module providing a full complement of batteries.
15 Dec 1999	4R	Russian	• Docking Compartment 1 (DC1)		• Docks to Service Module nadir. • Provide egress, ingress for Russian based Extravehicular Activity (AVA) and a Soyuz docking port.

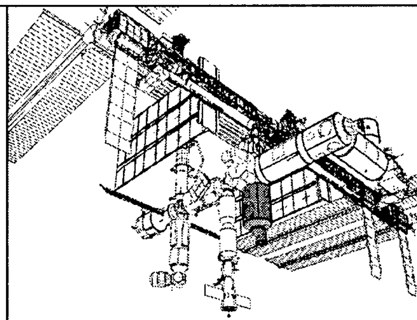
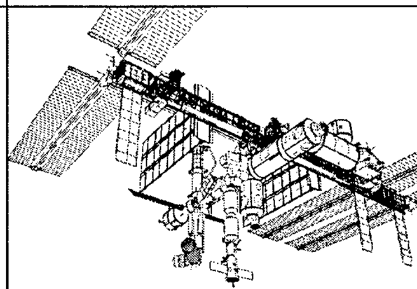
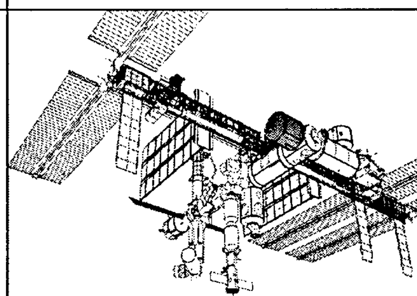
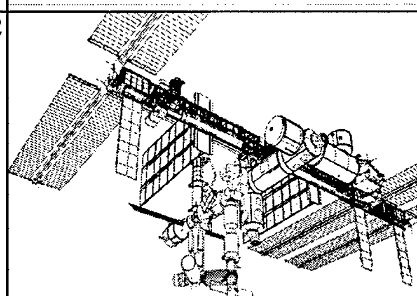
13 Jan 2000	UF-1	U.S. Orbiter (STS -104)	• MPLM w/Integrated International Payload Racks (ISPRs) • PV Module batteries		• Provides payload utilization delivering U.S. Lab ISPR racks; 2 stowage racks.
10 Feb 2000	8A	U.S. Orbiter (STS-105)	• ITS S0 • Mobile Transporter (MT) • GPS		• ITS S0 provides attachment and umbilical between pressurized elements and permanent truss-mounted distributed system/utilities. • Airlock spur provides an EVA translation path from the airlock to the truss. • The MT which provides the truss translation capability for the Mobile Servicing System is also delivered. • GPS antenna is deployed.
16 Mar 2000	UF-2	U.S. Orbiter (STS-106)	• MPLM (ISPRs) • MBS (Mobile remote servicer Base System) • Lab Sys.		• Provides additional payloads. • MBS provides truss based SSRMS capability. • Three additional stowage racks are delivered.
15 Jun 2000	9A	U.S. Orbiter (STS-108)	• ITS S1 • CETA Cart A		• Delivers the starboard U.S. Central Thermal control System • Radiators remain stowed until power system is activated on flight 12A. • Provides second string of S-band capability. • The CETA Cart provides EVA crew translation capability along the truss.

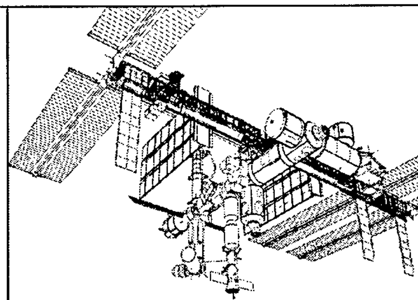
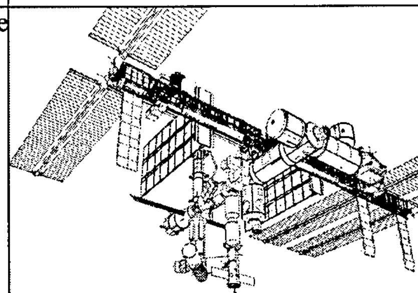
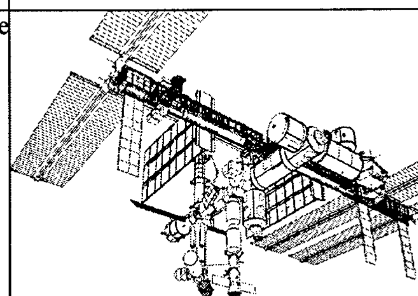
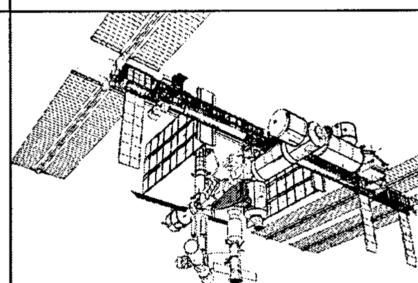
20 Jul 2000	9A.1	U.S. Orbiter (STS -109)	• SPP with four solar arrays		• Delivery of the Russian power/control mast with four solar arrays providing additional Russian power • Delivers European Robotic Arm (ERA)
26 Oct 2000	11A	U.S. Orbiter (STS -111)	• ITS P1 • CETA Cart B		• Delivers the port U.S. Central Thermal control System • Radiators remain stowed until power system is activated on flight 12A. • Provides second string of S-band capability. • The CETA Cart provides EVA crew translation capability along the truss.
30 Nov 2000	12A	U.S. Orbiter (STS -112)	• ITS P3/P4		• Provides additional U.S. power • Port & starboard central TCS radiators are deployed and activated. • Translation from early P6-based power to permanent truss-based power begins. • P4/P4 installed but not sun-tracking until P6 retracted.
15 Dec 2000	3R	Russian	• Universal Docking Module (UDM)		• Attaches to Service Module nadir; provides docking locations for Russian Research Modules, Life Support Modules and a second docking compartment (DC2) for Soyuz vehicles.

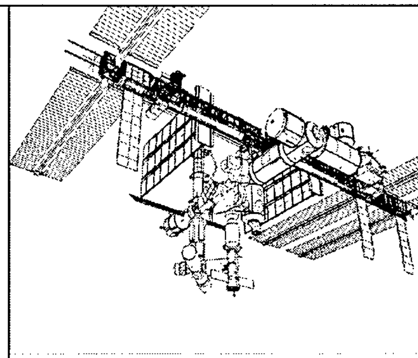
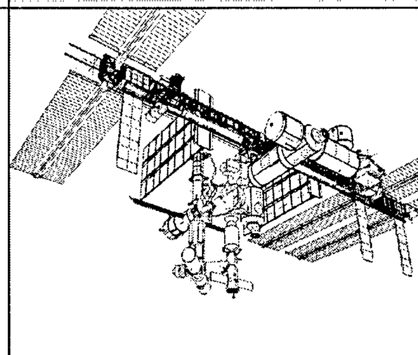
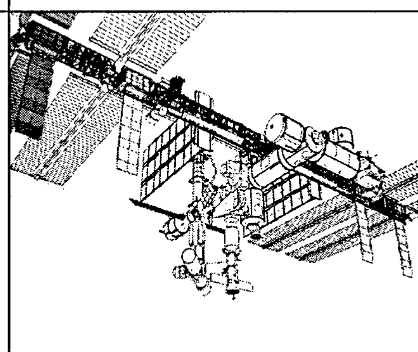
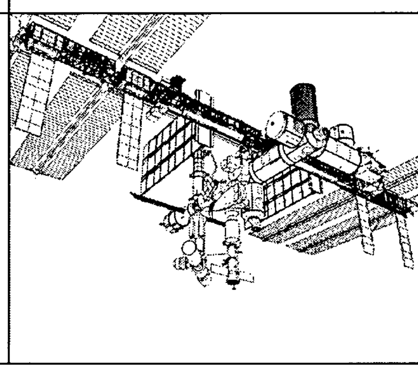
26 Dec 2000	5R	Russian	• Docking Compartment 2 (DC2)		• Docks to UDM (nadir); replaces discarded DC1.
15 Mar 2001	13A	U.S. Orbiter (STS-114)	• ITS S3/S4		• Provides additional U.S. power. • The P6 PV Module solar arrays are retracted on preparation for relocation on 1J/A.
12 Apr 2001	10A	U.S. Orbiter (STS-115)	• Node 2 • Nitrogen Tank Assembly (NTA)		• Node 2 provides attach locations for the Japanese Experiment Module, the ESA Columbus Orbital Facility, the Centrifuge Accommodation Module and later-mini-Pressurized Logistics Modules.
10 May 2001	1 J/A	U.S. Orbiter (STS-116)	• JEM ELM PS • ITS P5 • High Pressure 02 tanks		• Installs JEM ELM PS on Node 2 zenith. • Delivers 4 JEM systems racks and 1 stowage rack allowing 1 fault-tolerant JEM PM activation on the next flight. • 3 JEM ISPRs delivered providing utilization on the next flight. • ITS P5 spacer provides clearance between port PV modules enabling P6 PV module relocation.

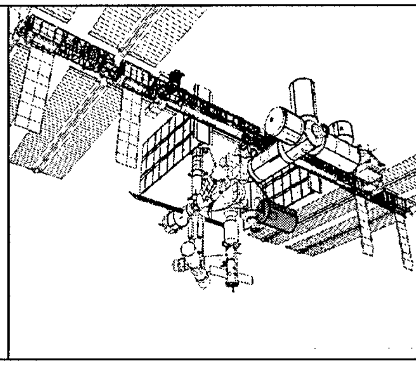
23 Aug 2001	1 J	U.S. Orbiter (STS-118)	• JEM PM • JEM RMS		• JEM PM installed on Node 2 portside. • Japanese Experiment Module is delivered & activated (4 JEM system racks). • JEM RMS is delivered & activated.
27 Sep 2001	UF-3	U.S. Orbiter (STS-119)	• MPLM (ISPRs)		• Provides for payload re-supply and/or change-out.
17 Jan 2002	UF-4	U.S. Orbiter (STS-121)	• Express Pallet • SLP SPDM, ATA, HP Gas)		• Express Pallet transports external payloads. • Spacelab Pallet (SLP) carries Special Purpose Dexterous Manipulator ("Canada Hand") provides robotics maintenance capability; Ammonia Tank Assembly (ATA); and High Pressure Gas O2 tank.
14 Feb 2002	2 J/A	U.S. Orbiter (STS-122)	• JEM EF • ELM ES • PV Module Batteries		• Delivers JEM exposed experimental facilities • PV batteries complete battery complements on PV modules P4 & S4.

28 Feb 2002	9R.1	Russian	• Docking & Stowage Module-1 (DSM1)		• Mounted to the FGB nadir port. • Provides additional on-orbit stowage and a Soyuz docking location.
01 May 2002	9R.2	Russian	• Docking & Stowage Module-2 (DSM2)		• Mounted to Docking and Stowage Module-1. • Provides additional on-orbit stowage and a Soyuz docking location.
23 May 2002	14A	U.S. Orbiter (STS-124)	• Cupola and Port Rails (on SLP) • 4 SPP Solar Arrays		• Cupola (Node 1,port) provides direct viewing capability for some robotics operations and payload viewing. • Completes Solar Power Platform solar arrays.
20 Jun 2002	UF-5	U.S. Orbiter (STS-125)	• MPLM (ISPRs) • Express Pallet		• Provides for payload re-supply and/or change-out. • Express pallet transports external payloads.

18 Jul 2002	20A	U.S. Orbiter (STS-137)	• Node 3		• Delivers Node 3 to be attached underneath Node 1. • Two avionics and 2 ECLSS racks delivered. • Node 3 provides attachment points for the U.S. Habitation Module, the Crew Return Vehicle and PMA-3.
23 Jul 2002	8R	Russian	• Research Module #1 (RM-1)		• Provides Russian experiments and research facilities.
24 Oct 2002	1E	U.S. Orbiter (STS-129)	• Columbus Orbital Facility		• European Space Agency (ESA) research facility provides additional research capability.
15 Nov 2002	10R	Russian	• Research Module #2 (RM-2)		• Provides Russian experiments and research facilities.

21Nov 2002	17A	U.S. Orbiter (STS-128)	• MPLM • Node, Lab racks		• Outfits Node 3 with 4 racks—2 Environmental Control and Life Support System racks and 2 Flight Crew Equipment racks (waste collection system and galley). • Three Crew Health Care System racks delivered. • Delivers 1 U.S. Lab rack, 1 stowage rack, ISPRs.
18 Jan 2003	11R	Russian	• Life Support Module 1 (LSM1)		• Progress Transfer Vehicle docks LSM1 to UDM nadir. • Life Support Module provides oxygen regeneration capability & other life support functions.
01 Mar 2003	12R	Russian	• Life Support Module 2 (LSM2)		• Progress Transfer Vehicle docks LSM2 to LSM1 nadir; then LSM1/LSM2 stack is moved to UDM port-aft location. • Life Support Module provides oxygen regeneration capability & other life support functions.
13 Mar 2003	18A	U.S. Orbiter (STS-131)	• CRV 1		• Crew Return Vehicle attached to the station provides additional 4-person crew-return capability added to already existing 3-person Soyuz crew return capability.

24 Apr 2003	19A	U.S. Orbiter (STS-132)	• MPLM		• Delivers 4 crew quarters racks to be placed in Node 2 and provide for transition to 6-person crew. • Delivers 6-U.S. stowage racks.
24 Jul 2003	15A	U.S. Orbiter (STS-134)	• PV Module S6		• Fourth U.S. truss-based PV module completing the major power system elements. • Starboard MT/CETA rails.
28 Aug 2003	UF-6	U.S. Orbiter (STS-135)	• MPLM (ISPRs)		• Provides for payload re-supply and/or change-out. • Delivers two photovoltaic batteries to complete station battery outfitting.
02 Oct 2003	UF-7	U.S. Orbiter (STS-136)	• Centrifuge Accommodations Module		• Centrifuge Accommodations Module attached to Node 2 zenith port enhances user research capabilities.

04 Dec 2003	16A	U.S. Orbiter (STS-126)	• U.S. Habitation Module		• Delivers U.S. Habitation Module to enhance crew accommodations.
PHASE THREE COMPLETE: OPERATIONAL LIFE-CYCLE BEGINS					

Note that flight numbers are often assigned to specific payloads for American (A), European (E), Russian (R), and Japanese (J). Because the order in which these payloads are manifested may change, the stages may not occur in numerical order for a given series. Thus, stage 10A follows stages 11A, 12A, and 13A. In addition, Progress, Soyuz, and some other docking flights are not listed in Table 2 due to the lack of introductory elements or orientation changes.

COORDINATE SYSTEMS

Before any aerospace vehicle control can be modeled, coordinate systems must be defined and differentiated. Due to the complexity of station construction, a number of different coordinate systems must be maintained to ensure integrity of the station during free flight, mating with other vehicles, and the addition of numerous components. The following sections define coordinate systems to describe ISS and U.S. Orbiter orientations in free or mated flight.

Local Vertical-Local Horizontal (LVLH) Coordinate System

The LVLH coordinate system is defined with the Z_{LO} axis pointing toward nadir (see Figure 2. The Y_{LO} axis points perpendicular to the orbital plane as a vector cross product of the radius and velocity vector. (Note the radius points from the vehicle to the geocentric center of the Earth. The X_{LO} axis is the horizontal projection of the velocity vector, a vector cross product of the y and z unit vectors, which defines the local horizontal axis. The center of this right-handed orthogonal system is located at the vehicle center of mass.

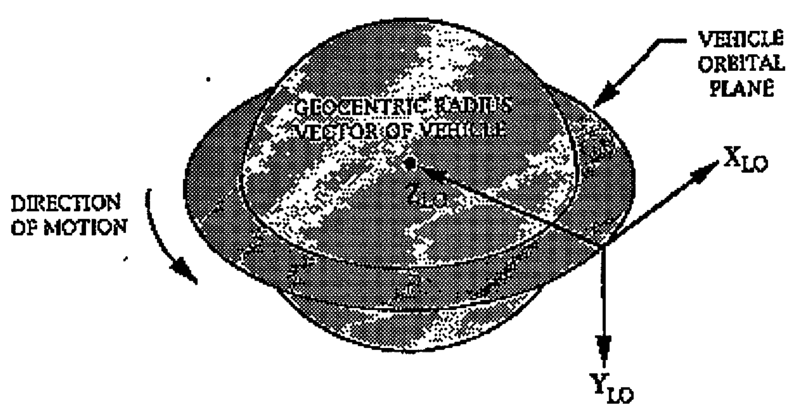


Figure 2:Local Vertical-Local Horizontal (LVLH) Coordinate System

Space Station Analysis Coordinate System

This system is a right-handed Cartesian, body-fixed coordinate system that corresponds to the LVLH flight orientation. The origin is located at the geometric center of the mid-ship truss (ITS S0). Figure 3 graphically represents this origin. The longitudinal x-axis of several core modules (Service Module, FGB, and Lab Module) is parallel with the analysis coordinate system axis X_A, positive in the direction of the velocity vector. The positive Y_A axis runs parallel with the starboard truss from the center point at S0. Axis Z_A completes the system, pointing toward nadir.

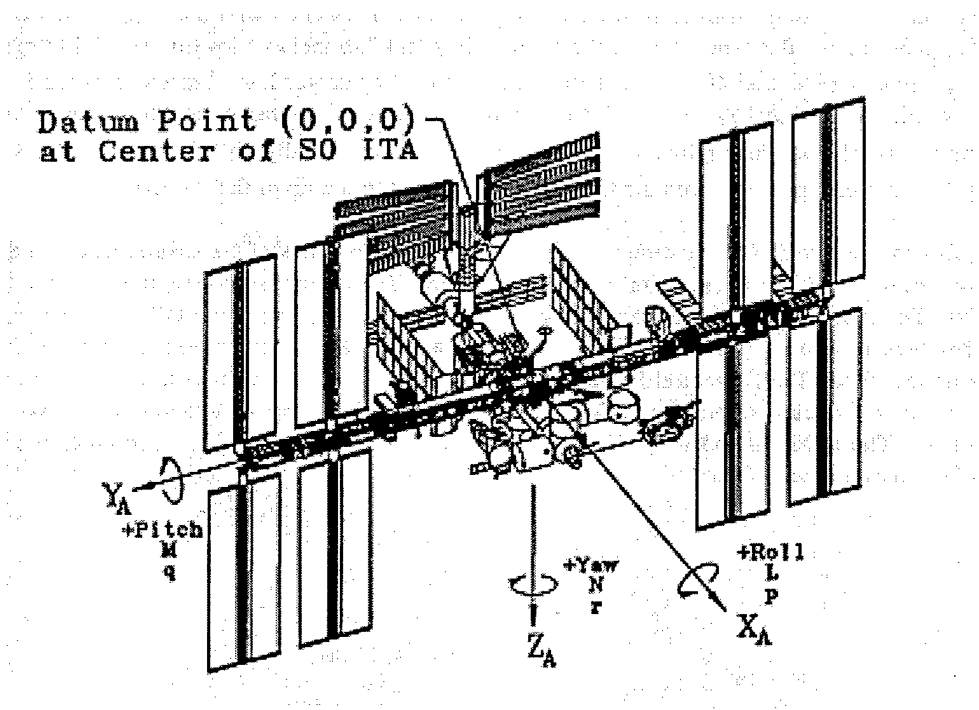


Figure 3: Space Station Analysis Coordinate System

Orbiter Structural Reference Frame

The Orbiter Structural Reference Frame is defined with the origin in the Orbiter plane of symmetry 400 inches below center line of the payload bay and 236 inches forward of the Orbiter nose (see Figure 4). The X_0 longitudinal axis runs parallel the payload bay centerline, directed positive from the vehicle's nose toward its tail. The vertical Z_0 axis is directed positive upward from the payload bay in the landing attitude. Finally, the Y_0 axis completes the right-hand system, directed from the Orbiter centerline out to the tip of the starboard wing.

Also present in Figure 4 are the different configurations of the Orbiter Docking System (ODS), whose location is critical in predicting the affects of Orbiter docking throughout various construction configurations. The ODS traverses through a number of [positions, most noteworthy of these is the Structural Lockup Position at Z=460", which represents the ODS interface extension when the Orbiter has securely docked to the ISS docking interface.

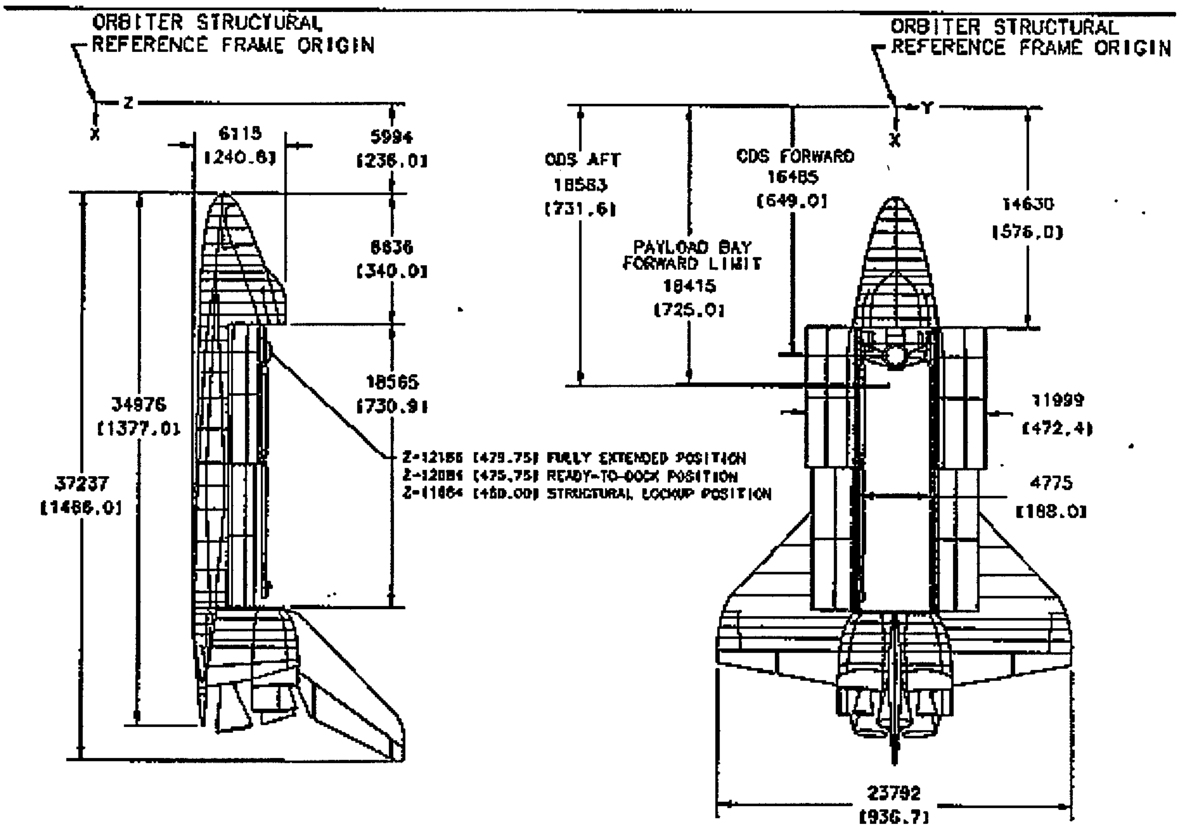


Figure 4: Orbiter Structural Reference Frame

Principal Axes Coordinate System

This body-fixed frame is defined when the products of inertia measured along such frame are equal to zero, leaving just the principle moments of inertia. The orientation of this right-handed frame is a function solely of geometry, and thus makes effects of torque and momentum very predictable. The origin lies at the object's center of mass. The principle axes are also used to define the major and minor axes of the body for rotational stability criteria.

RSA Analysis Coordinate System

The RSA (Russian Space Agency) Analysis System is a right-handed Cartesian, body - fixed coordinate system. The origin is located at the center of the aft side of the aft Service Module bulkhead. The coordinates of the RSA origin in the ISS coordinate systems are (-35360, 0, 4139) millimeters. The x-axis, X_R, is parallel to the x-axis of the ISS Coordinate System but is positive in the opposite direction of the velocity vector. The positive y-axis, Y_R, runs parallel to the SPP (Science Power Platform) core towards the SPP Solar Arrays. The Z-axis, Z_R, completes the triad.

The RSA Analysis Coordinate System will be used during early configurations of the construction process, in which components that locate the origin of the Space Station Analysis Coordinate System have yet to be in place. Hence, the RSA origin is located between the first ISS element, the Russian FGB (Functional Cargo Block), and the second element, the Russian Service Module.

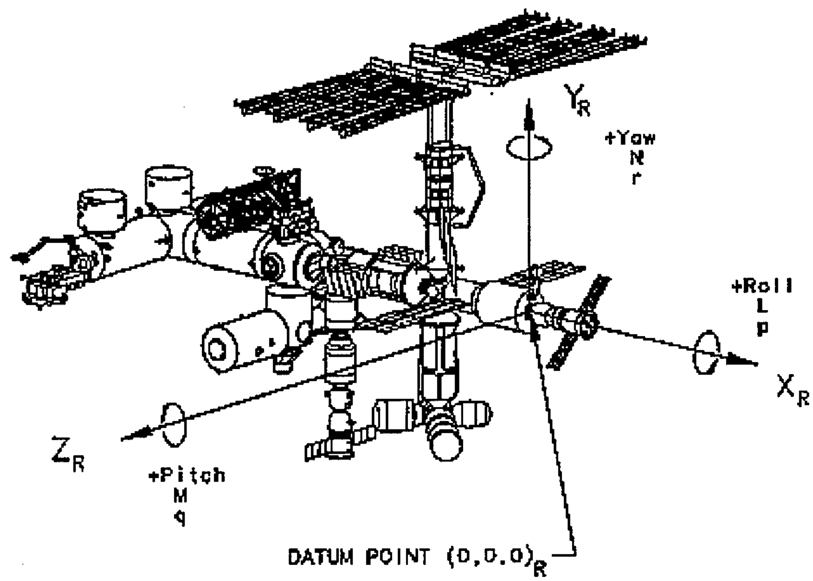


Figure 5: RSA Analysis Coordinate System

Table 3 is a quick-reference review of the many coordinate systems discussed in this paper.

Table 3: Various Coordinate Systems

Coordinate System	Reference Frame	Origin	Rationale/Use
Local Vertical-Local Horizontal System	X_{LO}, Y_{LO}, Z_{LO}	Center of vehicle mass	Astrodynamics
Space Station Analysis System	X_A, Y_A, Z_A	Center of ITS S0 truss	Primary coordinate system (U.S.)/ final configuration/ same of Nose, Right Wing, Down (NRD)
Orbiter Structural System	X_0, Y_0, Z_0	236 in beyond nose/400 in below bay centerline	Combining Shuttle/Station mass properties
Principle Axes System	P1, P2, P3	Center of mass	Simplify body dynamics
RSA Analysis System	X_R, Y_R, Z_R	FGB/Service Module connection	Early construction

INTEGRATED PRIME CONTRACTOR

If the ability to combine the resources of fifteen different nations can only be described as "delicate", then the effort to hoist the fruits of their labors (a mere 1 million pounds of hardware) would be indescribable. A construction timeline that lasts over 5 years can surely be tedious as its attention to detail is painstaking. Mere timelines, charts, and schematics cannot impart the sheer magnitude that is called the ISS construction process. The effort involves more than 100,000 people in space agencies and at hundreds of contractor and subcontractor companies around the world. Despite the fact these contractors are spread across 15 nations in the largest non-military joint effort in history, the need for centralized design and communication is crucial.

Enter Boeing, chosen as the Integrated Prime Contractor for the ISS. It is responsible for design, development, testing, verification and delivery of the United States on-orbit segment and FGB hardware and software. The Integrated Prime Contractor exercises direct management of all aspects of the Flight Elements and Subsystems (FE&S) as well as Krunichev contracts, including cost, schedule, and technical performance. In addition to all U.S. and Russian components, Boeing is responsible for analytical integration, verification, and certain top-level panning for the entire flight vehicle. Boeing responsibility also includes the on-orbit performance of the entire system throughout assembly and life cycle operation.

The FE&S refers to Boeings sub tier sites. They include Boeing, Huntingtion Beach, CA; Boeing North American, Canogo Park, CA; and Boeing Huntsville, AL. Approximately 258,900 pounds of U.S. flight hardware has been manufactured as of December 1997. Scheduled hardware completion in 1998 jump to over 500,000 pounds. "When you consider all the people, all the manufacturing facilities, all around the world, all producing one-of-a-kind space hardware that must come together out there in space and work perfectly the first time, it is phenomenal," says Doug Stone, vice president and space station program manager for The Boeing Company. "This is definitely outside the experience any of us have ever created before."

SEMDA LAB

Lockheed Martin Space Mission System & Services plays a vital role in assembly analysis. Located at Johnson Space Center, Houston, its Systems Engineering Modeling and Design Analysis Laboratory, or SEMDA Lab, provides a host of information to those involved in the assembly process. The SEMDA Lab creates computer models of all ISS elements and combines their properties to model various ISS configurations. The guidance, navigation, and control community utilize these models to perform their control analyses for the ISS, as well as other analysts with the ISS Program who require detailed mass properties.

Modeling ISS construction is one of the more challenging tasks for NASA planners. The Assembly process has been tweaked and refined many times leading up to its finalized Revision C Sequence. Analysis goes far beyond the 45 stages presented in Table 2, as they are only free-flying configurations after each stage's construction is complete. In actuality, every element, when added to the current station configuration, creates and entirely different vehicle, with its own specific dynamic properties.

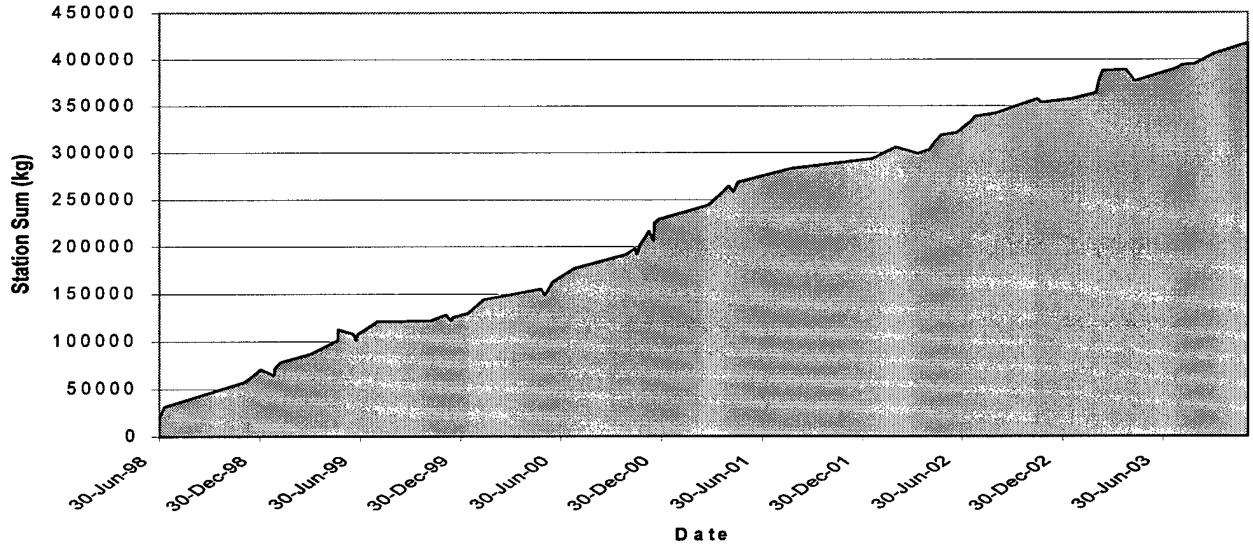


Figure 6: Mass of Free-Flying Configrations

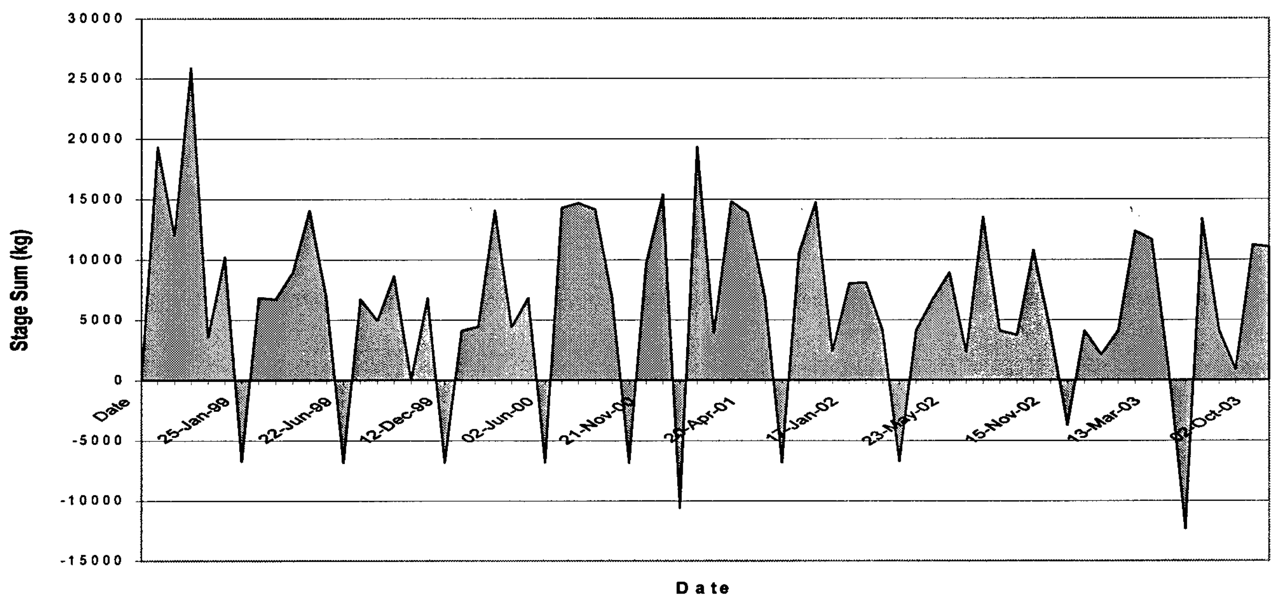


Figure 7: Net Mass-to-Oribt Throughout Assembly

Figure 6 shows the mass summary of the ISS chronologically in its free-flying modes. Figure 7 shows the mass summary of each flight. As seen in Figure 6, the ISS is constantly changing, and from Figure 7, one can see that the net change in mass will not always be positive. The negative sums are on dates in which Soyuz or Progress vehicles are scheduled for departure to remove crewmembers or unwanted material. Neither of the two includes the frequent Shuttle dockings, whose 204,117 pounds is surely to affect the structural properties of the station, especially in early stages.

These factors make Station control an ever-changing struggle. Table 4 is a list of all 112 different configurations that station managers will encounter throughout the current assembly sequence. This includes separate configurations for the ISS with the orbiter attached or free-flying. In addition, certain configurations depict the Station in free-flying modes before and after certain EVAs (Extra Vehicular Activity) or vehicle movements occur. Examples are given below:

STAGE	Assembly build or utilization launches. May be split into multiple configurations. Stage 16A is Assembly Complete.
FLIGHT	Intermediate launch or significant ISS geometry change. Never split into multiple configurations.
SZ-M	A FLIGHT showing ISS geometry changes after a Soyuz Movement.
SZ-R	A FLIGHT showing ISS geometry changes after a Soyuz Return to Earth.
+OAR	A STAGE configuration with the Orbiter attached; OAR – Orbiter After Rendezvous
+INT	A STAGE configuration with the Orbiter attached; INT – Intermediate
+OBS	A STAGE configuration with the Orbiter attached; OBS – Orbiter Before Separation
AS	A free flying configuration, after vehicle separation, but before further modification.

Additionally, names in boldface type indicate the free flying assembly operations complete configuration for a particular stage.

Table 4 : Configuration List

Conf. #	Stage/Flight & Configuration Name	Description of ISS Configuration
1	**STAGE 1A/R**	American-purchased launch 1 A/R, using Russian-built hardware (FGB Module).

2	STAGE 2A+OBS	Stage 1A/R+American launch 2A with attached Orbiter, just before Orbiter separates and returns.
3	**STAGE 2A**	Stage 1A/R+American launch 2A (Node 1, PMA 1, PMA 2).
4	**STAGE 1R**	Stage 2A+joint Russian launches 1R and 1P (Service Module, Progress) to aft FGB docking port.
5	STAGE 2A.1+OAR	Stage 1R+Amercian launch 2A.1 with attached orbiter immediately after rendezvous (fully loaded).
6	STAGE 2A.1+OBS	Stage 1R+Amercian launch 2A.1 with attached orbiter just before separation (fully loaded).
7	**STAGE 2A.1**	Stage 1R+Amercian launch 2A.1 (logistics & outfitting to FGB, SM, Node 1).
8	STAGE 3A+OAR	Stage 2A.1+American launch 3A with attached orbiter immediately after rendezvous (fully loaded).
9	STAGE 3A+INT	Stage 2A.1+American launch 3A with attached orbiter after Z1 placed on Node, PMA 3 still loaded.
10	STAGE 3A+OBS	Stage 2A.1+American launch 3A with attached orbiter just before separation (fully loaded).
11	**STAGE 3A**	Stage 2A.1+Amercian launch 3A (ITS Z1, PMA 3)
12	STAGE 1P-AS	Stage 3A+separation & return of first Progress
13	**STAGE 2R**	1P-AS+Russian launch 2R (first Soyuz TM {Transfer Module}). (1SZ)
14	FLIGHT 2P	Stage 2R+Russian servicing launch 2P (Progress M1). {Unloaded, separated, returned by 4A.}
15	STAGE 4A+OAR	Stage 2R+American launch 4A with attached orbiter after rendezvous. Progress (2P) removed.
16	STAGE 4A+INT	Stage 2R+American launch 4A with orbiter attached after P6 attached to Node, arrays/radiators stowed.
17	STAGE 4A+OBS	Stage 2R+American launch 4A with attached orbiter just before separation (fully unloaded).
18	**STAGE 4A**	Stage 2R+American launch 4A (ITS P6)
19	FLIGHT 1SZ-1	Stage 4A+First movement of 1SZ (2R) Soyuz vehicle. Done for reboost by Service Module.
20	STAGE 5A+OAR	Stage 4A+American launch 5A with attached orbiter immediately after rendezvous (fully loaded).
21	STAGE 5A+INT1	Stage 4A+American launch 5A with attached orbiter after PMA 2 moved to Z1 forward.
22	STAGE 5A+INT2	Stage 4A+American launch 5A with attached orbiter after Lab attached to Node, PMA 2 on Z1.
23	STAGE 5A+OBS	Stage 4A+American launch 5A with attached unloaded orbiter before separation, PMA 2 on Lab.
24	**STAGE 5A**	Stage 4A+American launch 5A (U.S. Laboratory Module).
25	FLIGHT 2SZ	Stage 5A+Russian Soyuz TM launch 2SZ (second crew transfer vehicle).
26	FLIGHT 2SZ-R1	2SZ+Separation & return of first Soyuz.

27	FLIGHT 4P	2SZ-R1+Russian servicing launch 4P (Progess M1).
28	STAGE 6A+OAR	4P+American launch 6A with attached orbiter immediately after rendezvous (fully loaded).
29	STAGE 6A+INT1	4P+American launch 6A with attached orbiter after fully laded MPLM attached to Node.
30	STAGE 6A+INT2	4P+American launch 6A with attached orbiter before unloaded MPLM removed from Node.
31	STAGE 6A+OBS	4P+American launch 6A with attached orbiter just prior to separation (fully unloaded).
32	**STAGE 6A**	4P+American launch 6A (Outfitting, SSRMS).
33	STAGE 7A+OAR	Stage 6A+American launch 7A with attached orbiter immediately after rendezvous (fully loaded).
34	STAGE 7A+OBS	Stage 6A+American launch 7A with attached orbiter just before separation (fully unloaded).
35	**STAGE 7A**	Stage 6A+American launch 7A (Airlock, HPGA).
	**** PHASE II COMPLETE – INITIAL SCIENCE CAPABILITY ****	
36	STAGE 7A.1+OAR	Stage 7A+American launch with attached orbiter after rendezvous (loaded). {Progress swap.}
37	STAGE 7A.1+OBS	Stage 7A+American launch with attached orbiter just before separation (fully unloaded).
38	**STAGE 7A**	Stage 7A+American launch (Logistics & Outfitting).
39	FLIGHT 3SZ	Stage 7A+Russian Soyuz TM launch 3SZ (third crew transfer vehicle).
40	FLIGHT 3SZ-R2	3SZ+Separation & return of second Soyuz.
41	**STAGE 4R**	3SZ-R2+Russian launch 4R (DC 1 {Docking Compartment #1}, Cargo Boom}.
42	STAGE UF1+OAR	Stage 4R+American Utilization Flight 1 (UF1) with attached orbiter immediately after rendezvous.
43	STAGE UF1+OBS	Stage 4R+American Utilization Flight 1 (UF1) with attached orbiter just before separation
44	**STAGE UF1**	Stage 4R+American Utilization Flight 1 (Outfitting, P6 Battery addition, OTDs).
45	STAGE 8A+OAR	Stage UF1+American launch 8A with attached orbiter immediately after rendezvous (fully loaded).
46	STAGE 8A+OBS	Stage UF1+American launch 8A with attached orbiter just before separation (fully unloaded).
47	**STAGE 8A**	Stage UF1+American launch 8A (ITS S0).
48	STAGE UF2+OAR	Stage 8A+American Utilization Flight 2 (UF2) with attached orbiter immediately after rendezvous
49	STAGE UF2+OBS	Stage 8A+American Utilization Flight 2 (UF2) with attached orbiter just before separation.
50	STAGE UF2-AS	Stage 8A+American Utilization Flight 2 (UF2) after separation; before certain robotic operations.
51	**STAGE UF2**	Stage 8A+American Utilization Flight 2 (Outfitting, MBS). PMA 3

		moved to Node 1 nadir.
52	FLIGHT 4SZ	Stage UF2+Russian Soyuz TM launch 4SZ (fourth crew transfer vehicle).
53	FLIGHT 4SZ-R3	4SZ+Separation & return of third Soyuz.
54	STAGE 9A+OAR	4SZ-R3+American launch 9A with attached orbiter immediately after rendezvous (fully loaded).
55	STAGE 9A+OBS	4SZ-R3+American launch 9A with attached orbiter just before separation (fully unloaded).
56	**STAGE 9A**	4SZ-R3+American launch 9A (ITS S1, TCS, CETA A).
57	STAGE 9A.1+OAR	Stage 9A+American launch 9A.1 with attached orbiter immediately after rendezvous.
58	STAGE 9A.1+OBS	Stage 9A+American launch 9A.1 with attached orbiter just before separation.
59	STAGE 9A.1-AS	Stage 9A+American launch 9A.1 after separation; before EVA activities (Stowed SPP Assembly).
60	**STAGE 9A.1**	Stage 9A+American launch 9A.1 (Deployed SPP Core, Arrays, Radiator, ERA); after EVA.
61	STAGE 11A+OAR	Stage 9A.1+American launch 11A with attached orbiter immediately after rendezvous (fully loaded).
62	STAGE 11A+OBS	Stage 9A.1+American launch 11A with attached orbiter just before separation (fully unloaded).
63	**STAGE 11A**	Stage 9A.1+American launch 11A (ITS P1, TCS, CETA B).
64	FLIGHT 5SZ	Stage 11A+Russian Soyuz TM launch 5SZ (fifth crew transfer vehicle).
65	FLIGHT 5SZ-R4	5SZ+Separation & return of fourth Soyuz.
66	FLIGHT 13P	5SZ-R4+Russian servicing launch 13P (Progress M1 on DC1, deploy & rotate S1 & P1 radiators).
67	STAGE 12A+OAR	13P+American launch 12A with attached orbiter immediately after rendezvous.
68	STAGE 12A+OBS	13P+American launch 12A with attached orbiter just before separation. (P4 arrays/radiators deployed.)
69	STAGE 12A-AS	13P+American launch 12A after separation; before separation activities.
70	**STAGE 12A**	13P+American launch 12A (ITS P3, ITS P4) after separation of Progress & DC1.
71	**STAGE 3R**	Stage 12A+Russian launch 3R (UDM {Universal Docking Module}). (12A EVAs not complete.)
72	**STAGE 5R**	Stage 3R+Russian Launch 5R (DC {Docking Compartment #2}). (12A EVAs not complete.)
73	FLIGHT 15P	5R+Russian servicing launch 15P (Progress M1 replaces M1). Retract two P6 radiators, port array.
74	STAGE 13A+OAR	15P+American launch 13A with attached orbiter immediately after rendezvous.
75	STAGE 13A+OBS	15P+American launch 13A with attached orbiter just before

		separation. Radiator move from P6 to S4.
76	STAGE 13A-AS	15P+American launch 13A after separation; before certain assembly activities.
77	**STAGE 13A**	15P+American launch 13A (ITS S3, ITS S4) after P6 starboard & FGB arrays, P6 radiator retracted.
78	STAGE 10A+OAR	Stage 13A+American launch 10A with attached orbiter immediately after rendezvous.
79	STAGE 10A+OBS	Stage 13A+American launch 10A with attached orbiter just before separation.
80	STAGE 10A-AS	Stage 13A+American launch 10A after separation; before robotic activities (Node 2 on Node 1).
81	**STAGE 10A**	Stage 13A+American launch 10A after Node 2 moved to Lab.
82	FLIGHT 6SZ	Stage 10A+Russian Soyuz TM launch 6SZ (sixth crew transfer vehicle).
83	FLIGHT 6SZ-R5	6SZ+Separation & return of fifth Soyuz.
84	STAGE 1J/A+OAR	6SZ-R5+American launch 1J/A with attached orbiter immediately after rendezvous (loaded).
85	STAGE 1J/A+OBS	6SZ-R5+American launch 1J/A with attached orbiter just before separation (fully unloaded, P6 to P5).
86	STAGE 1J/A-AS	6SZ-R5+American launch (w/NASDA hardware) 1J/A before certain assembly activities.
87	**STAGE 1J/A**	6SZ-R5+American launch 1J/A (O2, JEM ELM PS, P5) after all P1/S1 radiators deployed.
88	**STAGE 1J**	Stage 1J/A+American launch 1J, of NASDA hardware (EM Pressurized Module {PM}, JEM RMS).
89	**STAGE UF3**	Stage 1J+American Utilization Flight 3 (Outfitting).
90	**STAGE UF4**	Stage UF3+American Utilization Flight 4 (AMS, Express Pallet, SPDM); new Soyuz on FGB.
91	**STAGE 2J/A**	Stage UF4+American launch 2J/A (S4/P4 Batteries, JEM EF, JEM ELM ES).
92	**STAGE 9R.1**	Stage 2J/A+Russian launch 9R.1 (DSM 1 {Docking & Stowage Module #1}); move Soyuz to UDM.
93	**STAGE 9R.2**	Stage 9R.1+Russian launch 9R.2 (DSM 2 {Docking & Stowage Module #2}); new Soyuz on SM aft.
94	**STAGE 14A**	Stage 9R.2+American Launch 14A (SPP Arrays, cupola, Port MT Rails); move Soyuz to UDM.
95	**STAGE UF5**	Stage 14A+American Utilization Flight 5 (Outfitting, Express Pallet).
96	**STAAGE 20A**	Stage UF5+American launch 20A (Node 3); move PMA 3 to Hab nadir.
97	**STAGE 8R**	Stage 20A+Russian launch 8R (RM 1 {Research Module #1}); move Soyuz to DSM.
98	**STAGE HTV1**	Stage 8R_NASDA (Japanese) launch HTV1 {H-II Transfer Vehicle} (Outfitting).

99	**STAGE 1E**	Stage HTV1+American launch 1E (ESA COF {Columbus Orbital Facility}); new Soyuz on UDM.
100	**STAGE 10R**	Stage 1E+Russian launch 10R (RM 2 {Research Module #2}); move Soyuz to DSM.
101	**STAGE 17A**	Stage 10R+American launch 17A (Outfitting).
102	**STAGE 11R**	Stage 17A+Russian launch 11R (LSM 1 {Life Support Module #1} on UDM nadir).
103	**STAGE HTV2**	Stage 11R+NASDA (Japanese) launch HTV2 {H-II Transfer Vehicle} (Outfitting).
104	**STAGE 12R**	Stage HTV2+Russian launch 12R (LSM 2 {Life Support Module #2}). LSM 1 & LSM 2 relocation.
105	**STAGE 18A**	Stage 12R+American launch 18A (X-38 CRV#1); Progress on SM aft replaced by ATV #1.
106	**STAGE 19A**	Stage 18A+American launch 15A (ITS S6, Starboard MT Rails); Progress on SM aft replaces ATV #1.
107	**STAGE 15A**	Stage 15A+NASDA (Japanese) launch HTV3 {H-II Transfer Vehicle} (Outfitting).
108	**STAGE HTV3**	Stage 15A+NASDA (Japanese) launch HTV3 {H-II transfer Vehicle} (Outfitting).
109	**STAGE UF6**	Stage HTV3+American Utilization Flight 6 (Outfitting, S6 Batteries).
110	**STAGE UF7**	Stage UF6+American Utilization Flight 7 (CAM {Centrifuge Accommodations Module}); new Soyuz.
111	STAGE 16A+OBS	Stage UF7+American launch 16A with attached orbiter just before separation (fully unloaded).
112	**STAGE 16A**	Stage UF7+American launch 16A (Habitation Module).
**** PHASE III, ISS ASSEMBLY COMPLETE ****		

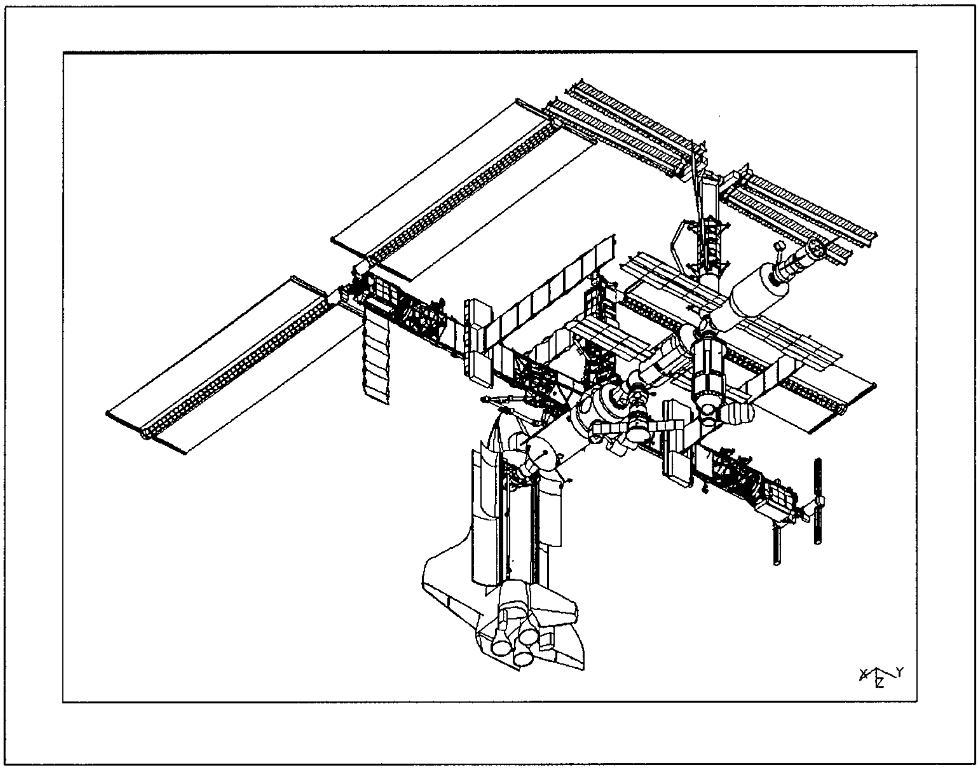


Figure 8: Stage 13A+OBS (Configuration 75)

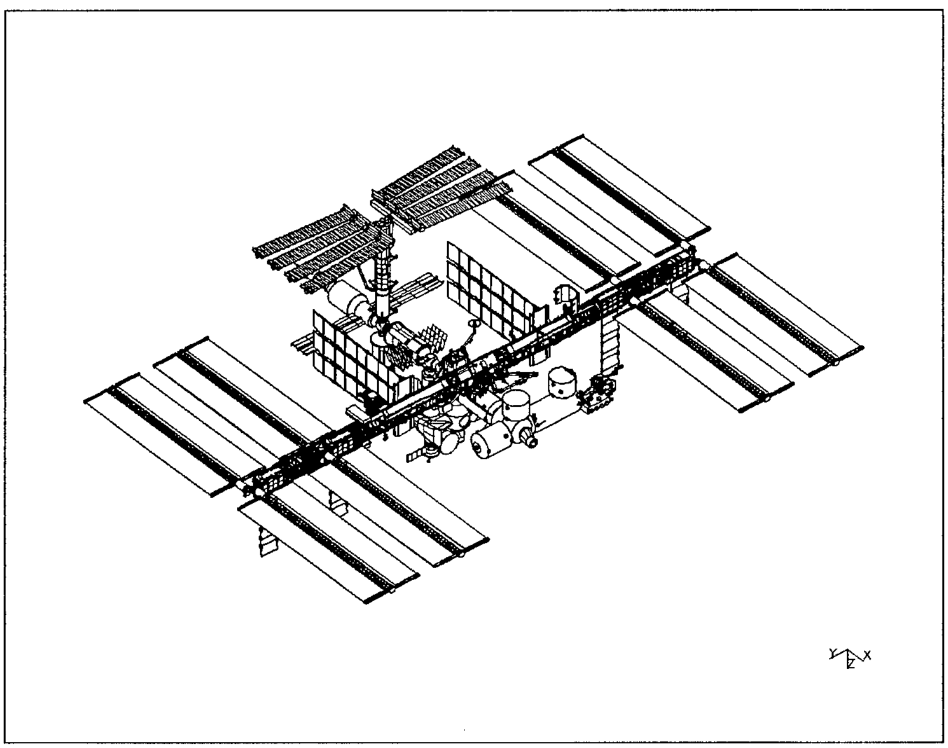


Figure 9: Stage 16A (Configuration 112)

SEMDA Lab's Design Analysis Cycle #6, the latest DAC based on Revision C, produced CAD models of all ISS elements and 112 configurations. Information produced is essential to CN&G (Control, Navigation & Guidance) personnel, such as total mass and center of mass. But most important to attitude control is the derivation of the inertia tensor.

DYNAMICS TOOLS

Moment of momentum of a rigid body about its center of mass is described as

$$\vec{h}_o = \int_B \vec{r} \times (\vec{\omega} \times \vec{r})dm \tag{1}$$

Subsequently,

$$\vec{\omega} \times \vec{r} = (\omega_y z - \omega_z y)\hat{i} + (\omega_z x - \omega_x z)\hat{j} + (\omega_x y - \omega_y x)\hat{k} \tag{2}$$

And,

$$\begin{aligned} \vec{r} \times (\vec{\omega} \times \vec{r}) &= [\omega_x (y^2 + z^2) - \omega_y (xy) - \omega_z (xz)]\hat{i} \\ &+ [-\omega_x (xy) + \omega_y (x^2 + z^2) - \omega_z (yz)]\hat{j} \\ &+ [-\omega_x (xz) - \omega_y (yz) + \omega_z (x^2 + y^2)]\hat{k} \end{aligned} \tag{3}$$

Integrating this form over the body dimensions is strictly a function of mass distribution, while components of angular velocity are independent of body shape and inertial location. Thus, any given rigid body can be characterized by a set of constants for the purpose of studying angular momentum and, eventually, attitude motion. These constants are defined as:

$$\begin{aligned} I_x &= \int_B (y^2 + z^2)dm \\ I_y &= \int_B (x^2 + z^2)dm \\ I_z &= \int_B (x^2 + y^2)dm \\ I_{xy} &= \int_B (xy)dm \\ I_{xz} &= \int_B (xz)dm \\ I_{yz} &= \int_B (yz)dm \end{aligned} \tag{4}$$

Where I_x, I_y, and I_z are called the moments of inertia of the body about the x, y, and z axes, respectively. I_{xy}, I_{xz}, and I_{yz} are called the products of inertia of the body. The products of inertia may have positive or negative values while the moments of inertia can never be negative.

These values generally presented in symmetric matrix form call the inertia tensor written as:

$$\begin{bmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{xy} & I_y & -I_{yz} \\ -I_{xz} & -I_{yz} & I_z \end{bmatrix} \tag{5}$$

The inertia tensor is used frequently to relate a body's mass and geometric properties with angular momentum, rotational kinetic energy, etc. To make calculations easier, you can find a body fixed reference frame that will make the inertia tensor a diagonal matrix ($I_{xy} = I_{xz} = I_{yz} = 0$). The resulting moments of inertia are called the principal moments of inertia and are designated I_1, I_2, and I_3. The coordinate axes of this special reference frame are called the principal axes. The transformation matrix that will transform any axes to the principal axes consists of a matrix of eigenvectors and the resulting diagonal inertia tensor will be a matrix of eigenvalues.

All these tools of dynamics and control can be applied to any configuration, as will now be exercised during an event in mid-July of the year 2000, the 17th of the 45 different major assembly flights.

DYNAMIC PROPERTIES ANALYSIS

Stage 9A.1 involves a joint US/RSA assembly flight in which the Orbiter delivers initial components of the RSA Science Power Platform (SPP). The Orbiter docks to PMA 2 on the U.S. Lab, forward axial port, with its tail toward nadir. For simplification, the U.S. Shuttle will be taken out of the analysis, so the only effects studied will be those caused by the addition of the Science Power Platform. Therefore, Configuration 57, Stage 9A.1+OAR, and Configuration 58, Stage 9A.1+OBS will be skipped, leaving only Configuration 56, Stage 9A and Configuration 59, Stage 9A.1-AS. Further EVAs are needed after Orbiter separation until Stage 9A.1 is complete (Configuration 60), but the analysis below only involves the addition of the Science Power Platform in its stowed form.

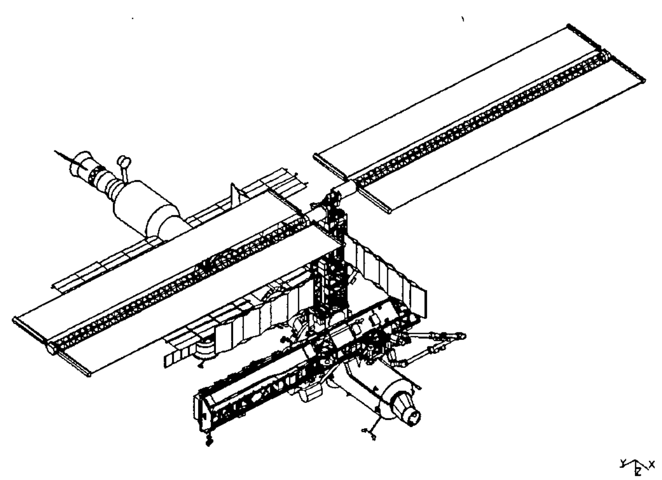


Figure 10: Stage 9A (Configuration 56)

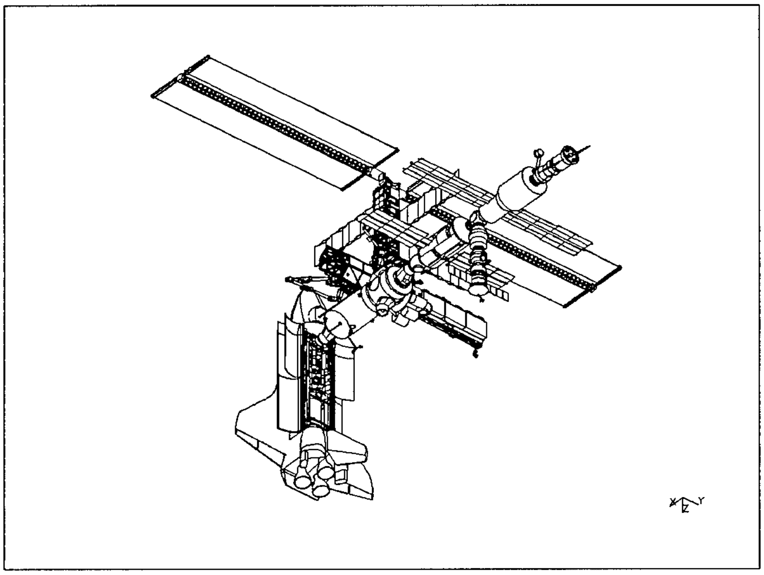


Figure 11: Stage 9A.1+OAR (Configuration 57)

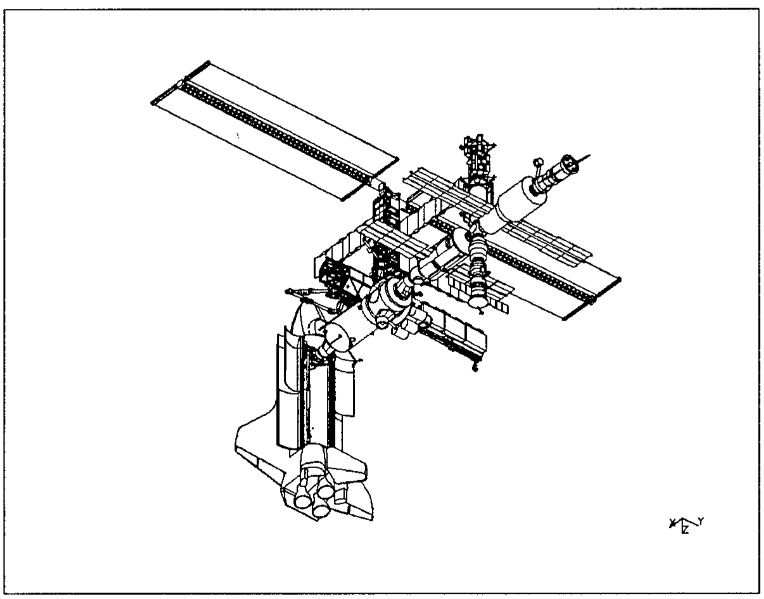


Figure 12: Stage 9A.1+OBS (Configuration 58)

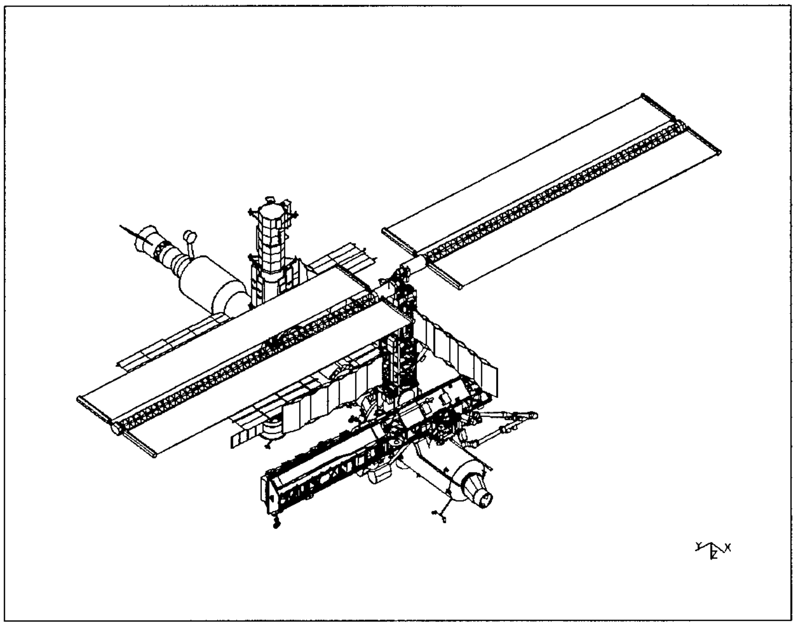


Figure 13: Stage 9A.1-AS (Configuration 59)

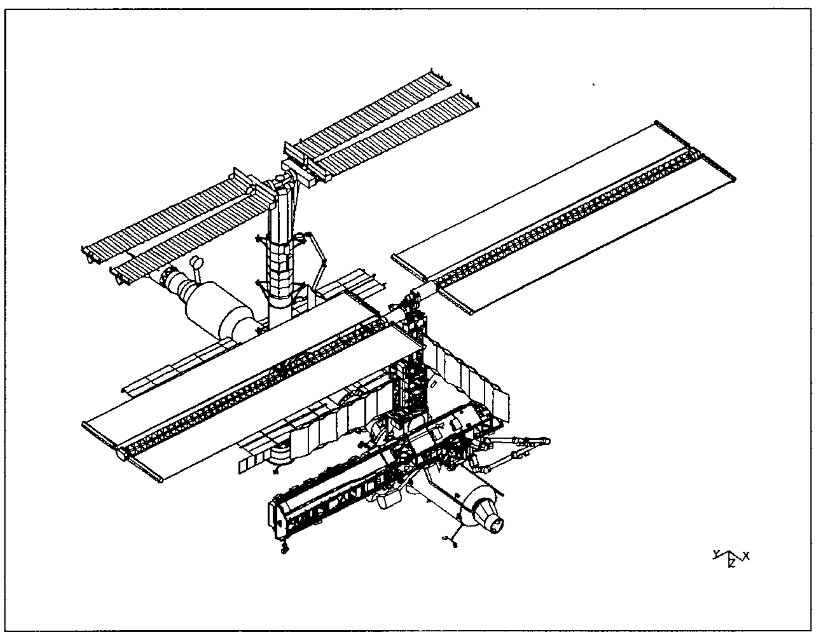


Figure 14: Stage 9A.1 (Configuration 60)

Figure 10 shows the completed and free-flying Stage 9A before any Stage 9A.1-activities begin. Figure 11 through Figure 14 display and clarify the sequential configurations for Stage 9A.1. The unique position and arrangements of the new element and Shuttle call for separate analysis of each stage, but since we desire just the effect of the SPP, configurations 57 and 58 will be omitted, as seen in the timeline below (those between the bold type).

Stage 9A → Stage 9A.1+OAR → Stage 9A.1+OBS → **Stage 9A.1-AS** → Stage 9A.1

Completed stage → Shuttle mates → SPP positioned → **Shuttle separates** → SPP deployed (Stage Complete)

Stage 9A.1 was chosen due to it limited number of new elements to the station (just the SPP). Furthermore, the large increase in mass will demonstrate the significant changes that occur with the addition of an element of such magnitude (14,700 kg onto an already 163,000 kg body).

The information desired at the end of our analysis is the change in the overall station's inertia tensor due to the addition of the SPP. For lack of time and computing power, I will use the inertia tensor from Stage 9A as my baseline, calculate the moments and products of inertia for Stage 9A.1-AS, and compare the results with those produced by Lockheed Martin's SEMDA Lab.

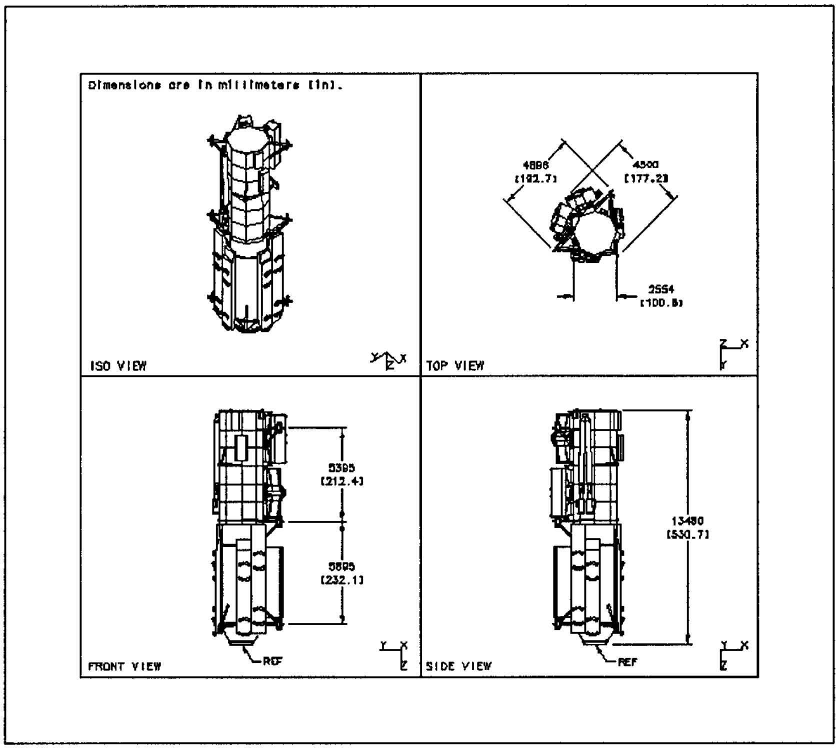


Figure 15: Science Power Platform in Stowed Position

The first step is to calculate the inertia tensor for the new element that is to be placed on the station. As you can in Figure 15, the Science Power Platform looks cylindrical while the solar arrays are retracted. Though it might be unclear from the figure, Lockheed denotes the SPP having a mass of 14,700 and a height of 13,480 mm. To calculate a radius, I averaged the three dimensions given due to the "blocky" attachments to the octagonal SPP. Note the coordinate frame, which has the z-axis running the length of the cylinder and the x and y-axes making up the axisymmetric directions. The origin of the body coordinates ("REF" in Figure 15) is at the center of the nadir APAS interface. When treated as a cylinder, the SPP's moments of inertia are quite simple:

$$I_x = I_y = \frac{1}{12}m\left(3r^2 + h^2\right) = \frac{1}{12}\times 14700kg \times \left(\left(3\times(1.991m)^2\right) + (13.480m)^2\right) = 237{,}295 kg\cdot m^2$$
$$I_z = \frac{1}{2}mr^2 = \frac{1}{2}\times 14700kg(1.991m)^2 = 29{,}400kg\cdot m^2 \tag{6}$$
$$I_{xy} = I_{yz} = I_{xz} = 0$$

Making its inertia tensor about its center of mass:

$$I = \begin{bmatrix} 237295 & 0 & 0 \\ 0 & 237295 & 0 \\ 0 & 0 & 29400 \end{bmatrix} kg\cdot m^2 \tag{7}$$

Two major assumptions went into the calculation of these properties: 1) the SPP is a perfect cylinder, and 2) the center of mass is in the geometric center of the cylinder, making the cylinder homogenous, and its mass uniformly distributed.

Complications arise when you try to combine these dynamic properties with the already existing Stage 9A. Moments and products of inertia can only be combined when they are measured about the same point. Since I've measured the object's inertia about its geometric center and the Station's is measure about *its* own center of mass, they are incompatible in this form.

The Parallel Axis Theorem solves this problem of non-equal origins.

$$
\begin{aligned}
I_x^o &= I_x^{\;b} + m\left(c_y^2 + c_z^2\right) \\
I_y^o &= I_y^{\;b} + m\left(c_x^2 + c_z^2\right) \\
I_z^o &= I_z^{\;b} + m\left(c_x^2 + c_y^2\right) \\
I_{xy}^o &= I_{xy}^{\;b} + m c_x c_y \\
I_{xz}^o &= I_{xz}^{\;b} + m c_x c_z \\
I_{yz}^o &= I_{yz}^{\;b} + m c_y c_z
\end{aligned}
\tag{8}
$$

The variable C denotes the vector from the point you want the inertia tensor measure about to the point where it is currently measured about. To find this vector from the center of mass of the ISS (point S) to the center of mass of the SPP (point B) requires a few more steps.

We know where the SPP's center of mass is in relation to the origin of the body coordinates (the REF in Figure 15). Aligned with the x and y-axes, point B is displaced by half the height of the SPP in the negative z direction, or 6740 mm. The ISS Mass Properties Databook also gives the body origin location in the ISS Analysis coordinate frame, as it is generally when the two bodies will be connected. Vector math leads to the equation:

Body Center (B) vector measured from Body Reference Point (REF) +

Body Refernce Point (REF) vector measured from ISS Origin (O) =

Body Center (B) vector measured from ISS Origin (O)

$$
\begin{bmatrix} 0 \\ 0 \\ -6740 \end{bmatrix} mm + \begin{bmatrix} -23722 \\ 0 \\ 3015 \end{bmatrix} mm = \begin{bmatrix} -23722 \\ 0 \\ -3725 \end{bmatrix} mm \tag{9}
$$

This would suffice if it weren't for the fact that the station's inertia tensor in not measured about the ISS Analysis origin (which is ideal for locating components), but it's center of mass, point S. NASA's ISS Databook lists the Station's center of mass for the previous stage, stage 9A at location X_A = -10.12 m, Y_A = 1.36 m, Z_A = 2.43 m. Remember though, that the center of mass has now changed due to the addition of the 14,700 kg Science Power Platform. The new center of mass of the station, S', has to be computed before the new inertia tensor can be found.

$$\bar{x} = \frac{\sum x_i m_i}{\sum m_i} = \frac{x_{station}\, m_{station} + x_{SPP}\, m_{SPP}}{m_{station}\, m_{SPP}} = \frac{-10.12\,m \times 162{,}645\,kg + (-23.772\,m) \times 14{,}700\,kg}{162{,}645\,kg + 14{,}700\,kg} = -11.24\,m \quad (10)$$

Applying the same equation for the y and z-components yield the new center of mass, S', in ISS coordinates.

$$\bar{y} = \frac{1.36m \times 162{,}645kg + 0m \times 14{,}700kg}{162{,}645kg + 14{,}700kg} = -1.25m$$

$$\bar{z} = \frac{2.43m \times 162{,}645kg + (-3.725m) \times 14{,}700kg}{162{,}645kg + 14{,}700kg} = 1.92m \quad (11)$$

Now that we know point S' in ISS coordinates, as well as point B in ISS coordinates, we can find the vector that from point S' to point B.

Body Center of Mass (B) measured from ISS Origin (O) –

Station's New Center of Mass (S') measured from ISS Origin (O) =

Body Center of Mass (B) measured from Station's New Center of Mass (S')

$$\begin{bmatrix} -23.722 \\ 0 \\ -3.725 \end{bmatrix} m - \begin{bmatrix} -11.24 \\ 1.25 \\ 1.92 \end{bmatrix} m = \begin{bmatrix} -12.482 \\ -1.25 \\ -5.645 \end{bmatrix} m \quad (12)$$

Using the Parallel Axis Theorem with this newly acquired information yields our new inertia tensor.

$$
\begin{aligned}
I_x^o &= I_x^b + m_b\left(c_y^2 + c_z^2\right) = 237295 + 14700\left((-1.25)^2 + (-5.645)^2\right) = 728694\ kg\cdot m^2 \\
I_y^o &= 237295 + 14700\left((-12.482)^2 + (-5.645)^2\right) = 2995990 \\
I_z^o &= 29400 + 14700\left((-1.25)^2 + (-1.25)^2\right) = 2342633 \\
I_{xy}^o &= 0 + 14700(-12.482)^2(-1.25)^2 = 229357 \\
I_{xz}^o &= 0 + 14700(-12.482)^2(-5.645)^2 = 1065648 \\
I_{yz}^o &= 0 + 14700(-1.25)^2(-5.649)^2 = 103800
\end{aligned}
\tag{13}
$$

Now the inertia of the SPP about the station's new center of mass can be added to the Station inertia from the previous stage to yield Configuration 59 properties.

$$
\begin{gathered}
I_{stage9A} + I_{SciencePowrPlatform} = I_{stage9A.1} \\
\begin{bmatrix} 8291774 & -2088184 & 3263206 \\ -2088184 & 30111546 & 386274 \\ 3263206 & 386274 & 29995958 \end{bmatrix} + \begin{bmatrix} 728694 & -229357 & -1065648 \\ -229357 & 2995990 & -103800 \\ -1065648 & -103800 & 2342633 \end{bmatrix} = \\
\begin{bmatrix} 9020468 & -2317541 & 2197558 \\ -2317541 & 33107536 & 282474 \\ 2197558 & 282474 & 32338591 \end{bmatrix} kg\cdot m^2
\end{gathered}
\tag{14}
$$

Again, if the products of inertia are zero, the principal moments of inertia will remain on the diagonal. They are also the eigenvalues of the inertia tensor. Using Matlab v 4.0, the principal moments of inertia for this new matrix are:

$$
\begin{aligned}
I_1 &= 8{,}593{,}000 \\
I_2 &= 33{,}335{,}000\ \ (kg\cdot m^2) \\
I_3 &= 32{,}538{,}000
\end{aligned}
\tag{15}
$$

The following table compares my calculations to those performed by Lockheed Martin's SEMDA Lab.

Table 5: Analysis Comparison

Parameter	Lockheed Martin's Systems Engineering Modeling and Design Analysis Laboratory	UCCS Masters of Engineering Student	Percent Error
Stage 9A.1 Center of Mass (m)	$X_A = -12.24$ $Y_A = 1.25$ $Z_A = 1.93$	$X_A = -12.24$ $Y_A = 1.25$ $Z_A = 1.92$	0 0 0.51
Stage 9A.1 Inertia Tensor ($kg{\cdot}m^2$)	$I_x = 9{,}010{,}859$ $I_y = 33{,}301{,}176$ $I_z = 32{,}526{,}662$ $I_{xy} = 2{,}338{,}366$ $I_{xz} = -2{,}152{,}867$ $I_{yz} = -274{,}965$	$I_x = 9{,}020{,}468$ $I_y = 33{,}107{,}536$ $I_z = 32{,}338{,}591$ $I_{xy} = 2{,}317{,}541$ $I_{xz} = -2{,}197{,}558$ $I_{yz} = -282{,}474$	0.1 0.58 0.58 0.89 2.07 2.73
Stage 9A.1 Principal Moments of Inertia ($kg{\cdot}m^2$)	I_1=8,591,202 I_2=33,530,140 I_3=32,717,358	I_1=8,593,000 I_2=33,335,000 I_3=32,538,000	0.02 0.58 0.55

As you can see, my calculations we extremely close to what NASA is using for control and guidance of the ISS. Altough I used the previous stage's center of mass and inertia tensor, the goal of the analysis was to find the change in these values due to the SPP's assembly, which from the table, was reproduced with astonishing accuracy (less than 1 percent error).

Naturally, doing these calculations by hand for over 100 configuration has its limitations. With the aid of powerful modeling programs, elements can be rearranged and assembled in different sequences in record time. Of course, it is the tools of the analysis exercised above which gives computer modeling its accuracy. The process presented above can be reproduced for any configuration and additional hardware.

GRAVITY GRADIENT STABILTY

Gravity gradient stabilization is a technique employed by certain satellite for maintaining orientation. Gravity gradient stabilization is generally used for keeping sensors, antennas and the like pointed toward the Earth. This is also true for the International Space Station. Though Earth observation is not it's primary mission, the ISS will attempt to keep its body-frame (X_A, Y_A, Z_A) aligned with the ever-changing orbit frame. This can be done by keeping the body, or Nose-Right Wing-Down (NRD) frame aligned with the orbit, or Tangential-Normal-Radial (TNR) frame.

The orbit frame (TNR frame) will rotate about the Normal vector with some angular velocity, which when evaluated for a circular orbit is:

$$\omega_o^2 = \frac{v_{cs}^2}{R_o^2} = \frac{\sqrt{\frac{\mu}{R_o}}}{R_o^2} = \frac{\mu}{R_o^2} \tag{16}$$

After much derivation, the net torque on a body can be found, once the easily-measured R_o vector in the TNR frame has been converted to the NRD frame by a series of 3-2-1 rotations through θ (pitch), ψ (yaw), and ϕ (roll).

$$T_{NET} = 3\omega_o^2 \begin{bmatrix} \phi(I_3 - I_2) \\ -\theta(I_1 - I_3) \\ -\phi\theta(I_2 - I_1) \end{bmatrix}^{NRD} \tag{17}$$

It is here that the terminology must change for for the remainder of the analysis. The above calcuations assume that the body's principal axes are aligned with the body's NRD frame, such a simple cylinder, box, or disk—and it is the NRD frame that is misaligned with the orbit's TNR frame. The ISS's principal frame is not aligned with its body NRD frame, but the NRD will always be aligned with TNR. We will still find the torque about the body's roll, pitch, and yaw axes, but the signs on the Euler angles will be reversed, since we'll be doing a 1-2-3 principal to body (the set of rotations provided by Lockheed's SEMDA Lab), instead of a 3-2-1 TNR to NRD.

Coverting the body rotation, ω, which is meausred in the TNR frame with respect to inertial space (since it's defined by the size of the orbit), to the body's NRD frame with the same set of rotations transforms Euler's Moment Equations from:

$$\begin{aligned} I_1\dot{\omega}_1 + (I_3 - I_2)\omega_2\omega_3 &= 3\omega_o^2(I_3 - I_2)\omega \\ I_2\dot{\omega}_2 + (I_1 - I_3)\omega_1\omega_3 &= -3\omega_o^2(I_1 - I_3)\theta \\ I_3\dot{\omega}_3 + (I_2 - I_1)\omega_1\omega_2 &= 0 \end{aligned} \tag{18}$$

into something less pretty, but more usable, as seen in equation 19.

$$\begin{aligned} I_1\ddot{\phi} + (I_2 - I_3)\phi\omega_o^2 + (I_2 - I_1 - I_3)\omega_o\dot{\psi} &= 3\omega_o^2(I_3 - I_2)\phi \\ I_2\ddot{\theta} &= -3\omega_o^2(I_1 - I_3)\theta \\ I_3\ddot{\psi} + (I_2 - I_1)\omega_2^2\psi - (I_2 - I_1 - I_3)\omega_o\dot{\phi} &= 0 \end{aligned} \tag{19}$$

Though visually unappealling, these equations tell us a lot about the body's changing orientation about roll, pitch and yaw. Note that pitch motion is uncoupled from roll and yaw, so it is stable if the criteria in equation 20 exists.

$$\frac{3\omega_o^2(I_{roll} - I_{yaw})\theta}{I_{pitch}} > 0 \tag{20}$$

Roll and yaw motion is obviously coupled, but linear. To make things easier, the constants have been replaced with single variables.

$$K_R = \frac{(I_2 - I_3)}{I_1} \quad K_Y = \frac{(I_2 - I_1)}{I_3} \tag{21}$$

Replacing some terms in the equations of motion with these variables yield:

$$\begin{aligned} \ddot{\phi} + 4\omega_o^2 K_R \phi + \omega_o (K_R - 1)\dot{\psi} &= 0 \\ \ddot{\psi} + \omega_o^2 K_Y \psi + \omega_o (1 - K_Y)\dot{\phi} &= 0 \end{aligned} \tag{22}$$

The characterisitc equation after a Laplace transform is:

$$s^4 + [1 + 3K_R + K_R K_Y]\omega_0^2 s^2 + 4K_Y K_R \omega_0^4 = 0 \tag{23}$$

Since every constant in the above equation is known, it can be put into transfer function form kF(s)=-1 and plotted onto a root locus, which will then visually display the stability of body given its geometry and orbit. The transfer function is:

$$\frac{K\left(s^2 + \dfrac{4K_Y\omega_o^2}{3 + K_Y}\right)}{s^2\left(s^2 + \omega_o^2\right)} = -1 \tag{24}$$

where the gain, K, is defined as:

$$K = K_R (3 + K_Y)\omega_0^2 \tag{25}$$

GRAVITY GRADIENT ANALYSIS

With these tools, the stability of every configuration during ISS construction can be analyzed. Knowing that the ISS will orbit at a little more than 407 km, ω^2 equals 1.26×10^{-6} radians/second. The principal moments of inertia and Euler angles for a 1-2-3 sequence from the princicple to the body frame were entered into a spreadsheet using Microsoft Excel. It calculated the net toque on the body in the roll, pitch, and yaw directions using equation 17.

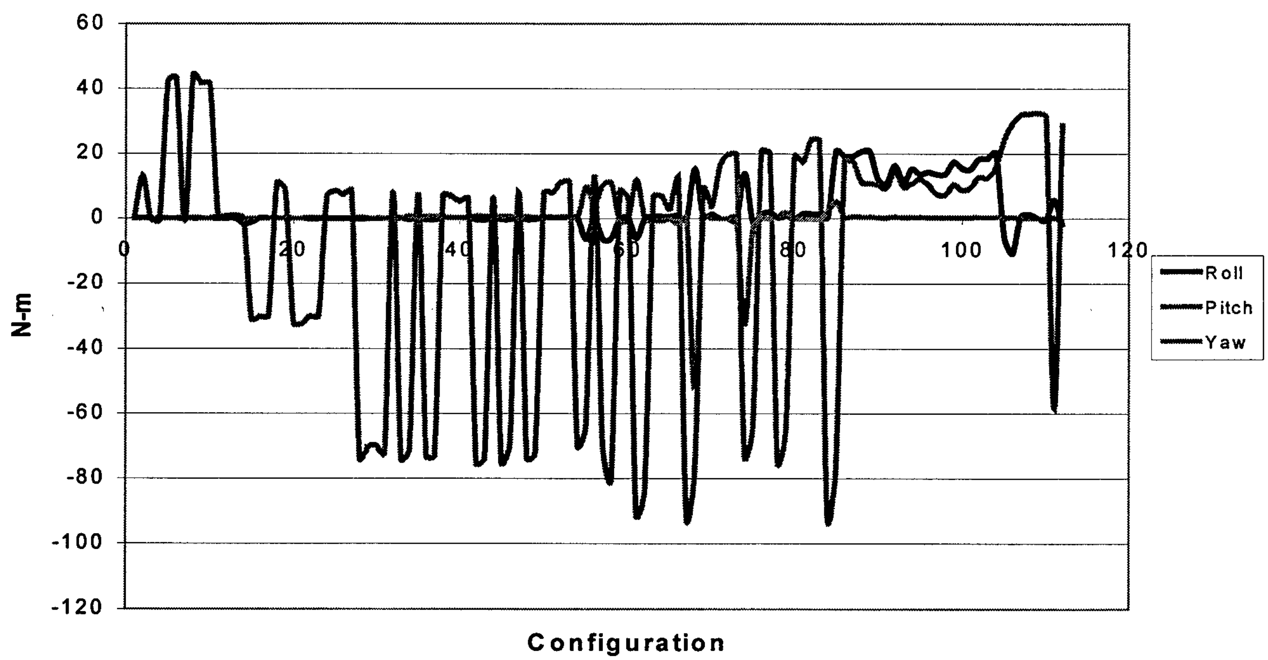


Figure 16: Net Torque due to Gravity Gradient

As you can see, the lagest torque due to gravity is the torque around pitch. Notice the very large, cyclic nature of the pitch torque that repeats every 2-3 configurations. Every steep increase in torque corresponds to the mating between the ISS and the Space Shuttle. At some instances, the torque measures over 80 N·m. This is quite large compared to the value normal experienced by smaller satellites, generally around 10^{-5} N·m. Of course you would have to consider the fact that these large torque might have little effect on a million pound space station.

But note that these large torques occur very early in the assembly process ($\approx$ config.30), when the ISS is far from its finished weight and inertia.

Small angle assumption was employed for calculate net torque, and since torque about yaw (ψ), has a higher-order term, $\phi\theta$, it may be eliminated all together. The net torque about yaw in Figure 16 is nevertheless very small when compared to pitch and roll.

The principal moments of inertia for the ISS are very large, the the SEMDA lab information was very accurate. Since the probability of two inertia being equal down to the 8th digit was very remote, symmetry was measured to within 5% of the inertia values. For example, configuration 3 yields an I_1, I_2 and I_3 of 77979, 1259725 and 1274509 kg·m^2, respectively. A 25,000 kg·m^2 difference is normally quite significant, but given the imposed 5% range of symmetry, the principal moment are ranked as $I_2=I_3>I_1$, instead of $I_3>I_2>I_1$.

Under this criteria, 14 out of 112 configuration were classifyed as "axisymmetric". Of these axisymmetric cases, all resembled a cylinder and none can be treated as disk-shaped. The remaining 98 configurations have significantly different inertia, resembling prism, box, or rectangle geometry. No configurations were considered "symmetric" (resembling a cube or sphere).

Equation 20 was employed for every configuration and returned a "yes" or "no" for pitch stability. Forty of the 112 configurations are unstable for pitch. Nearly all were during a configuration with an attached Oribter. The Shuttle actually improves stability in the early stages of assembly. Very shortly, though, the Oribter begins a repeating series of configurations unstable for pitch.

For roll/yaw analysis, it was nescessary to calculate K_Y, K_R, and K. Both K_R and K were forced to zero for all axisymmetric cases in which I_2=I_3. Knowing whether these coefficents in the transfer function were positve or negative, it was possible to know the general shape of the root locus for all possible gains. Of 112 configurations, 53 are classified as "Always Stable" for roll and yaw. Of the remaining 59, 14 are "Always Marginally Stable", 24 are "Marginally Stable for Small K, then Unstable", and 21 are classified as "Always Unstable". Table 6 is an example of the analysis for Configurations 76 to 86.

Table 6: Stability Analysis Sample

	Euler Angles (degrees)			Principal Moments of Inertia (kg·m^2)			Net Torque (kg·m^2/sec^2)		
Conf	ϕ (roll)	θ (pitch)	ψ (yaw)	I_1	I_2	I_3	$T_{\phi(roll)}$	$T_{\theta(pitch)}$	$T_{\psi(yaw)}$
76	-0.79	-10.06	-4.4	42002216	48172056	72763440	1.297812	20.673	-0.05717
77	-1.17	-9.51	-2.47	41643768	48989868	73036664	1.879511	19.94407	-0.0953
78	-0.56	21.11	-0.17	60934648	108430800	113692952	0.196858	-74.4014	0.654657
79	-1.75	19.96	-0.3	61199008	104186160	110215000	0.704813	-65.3582	1.750719
80	0.04	-9.12	1	42328288	49521804	73939376	-0.06525	19.25911	0.00306
81	-0.88	-7.03	-1.27	42056508	55032328	78699072	1.391307	17.2085	-0.09359
82	-0.97	-9.84	-1.12	43749800	58671616	80653112	1.424396	24.25841	-0.16606
83	-0.97	-9.71	-1.11	43564128	58442444	80603904	1.436058	24.02644	-0.16339
84	-1.26	17.03	-0.04	62256888	139146288	143116352	0.334172	-91.9914	1.923671
85	-7.66	14.26	-0.68	92076968	132330608	172694208	20.65478	-76.7979	5.126638
86	-4.83	-6.25	-23.57	75779752	58597860	117811088	19.10591	17.54911	0.604752

Conf	AntiSym	AxiSym	Sym	Stable for Pitch?	K_Y	K_R	K	Stability in Roll/Yaw
76	I1<I2<I3			YES	0.0847931	-0.585478	-2E-06	Always Unstable!
77	I1<I2<I3			YES	0.100581	-0.57744	-2E-06	Always Unstable!
78		I2=I3>I1		NO	0.4177581	0	0	Always Marginally Stable
79	I1<I2<I3			NO	0.39003	-0.098512	-4E-07	Always Unstable!
80	I1<I2<I3			YES	0.0972894	-0.576862	-2E-06	Always Unstable!
81	I1<I2<I3			YES	0.1648789	-0.562737	-2E-06	Always Unstable!
82	I1<I2<I3			YES	0.1850123	-0.502436	-2E-06	Always Unstable!
83	I1<I2<I3			YES	0.1845856	-0.508709	-2E-06	Always Unstable!
84		I2=I3>I1		NO	0.537251	0	0	Always Marginally Stable
85	I1<I2<I3			NO	0.233092	-0.438368	-2E-06	Always Unstable!
86	I2<I1<I3			YES	-0.145843	-0.781386	-3E-06	Marginally stable for small K, then Unstable

The complete table for all 112 configurations can be found in the appendix. The below table is a break down of gravity graident stabilty for its 5-year construction.

Table 7: Stability Breakdown

Pitch Stability	Roll/Yaw Stability
72 *Stable*	24 *Always Stable*
	9 *Always Marginally Stable*
	24 *Marginally Stable for small K, then Unstable*
	15 *Always Unstable*
40 *Unstable*	30 *Always Stable*
	5 Always Marginally Stable
	0 *Marginally Stable for small K, then Unstable*
	6 *Always Unstable*

From Table 7, one can conclude that only 24 configurations are stable for pitch, roll, and yaw. This does not mean that the remaining 88 configurations are completely unstable and doomed to catasrophic uncontrollability. It just implies that more resources, such as reaction wheel size and power, must be employed to keep the ISS in its desired orientation. Control algotrithms will need to be emmensly complex and require dilgent attention.

Eventually, the ISS will be complete and Shuttle will redezvous with th Station regularly, yet the Station's dynamic metamorphasis will continue. The ISS will also dock with Russian Soyuz and Progress Modules, but the Shuttle, due to its size and mass, has the greatest effect on the ISS. This can be seen in the analysis between Configuration 111 (Stage 16A+Orbiter Before Separation) and Configuration 112 (Stage 16A). The below table highlights some of the more significant changes due to mated operations.

Table 8: Effects of the Space Shuttle on ISS Dynamics

Conf	ϕ_{roll}	θ_{pitch}	ψ_{yaw}	T_{Roll}	T_{Pitch}	T_{Yaw}	Inertia Rank	Stable for Pitch?	Stability in Roll/Yaw
111 (16A+OBS)	-1.12	10.0	8.3	5.65	-58.0	0.14	$I_1<I_2<I_3$	NO	Always Unstable!
112 (16A)	0.37	-7.25	-3.26	-2.35	29.52	-0.11	$I_2<I_1<I_3$	YES	Marginally Stable for small K, then Unstable

The changes due to Shuttle docking are great and span the spectrum of dynamics. The principal axes rotate almost 20 degrees for pitch as the shuttle drags the principal frame that was once above the x-y plane of the station to more than 10 degrees below. The torque about the station's pitch also transitions not only in magnitude, but direction. The inertia ranking is also significant. The ISS is constantly rotating about pitch (I_2) to keep Z_A pointed toward nadir. When free-flying, the Station rotates about its minor axis. This is not as preferred by the Station's geometry as is it's major axis, but it is somewhat stable. Once the Shuttle docks in its usual position, the front tip of the ISS, it is now spinning about its intermediate axis, a difficult (if not impossible) task to maintain. Stability about pitch, roll and yaw also degrades when the Orbiter is joined.

ROOT LOCUS VERIFICATION

The root locus stability analysis method is one technique in control theory. Again, the transfer function is:

$$\frac{K\left(s^2+\dfrac{4K_Y\omega_o^2}{3+K_Y}\right)}{s^2\left(s^2+\omega_o^2\right)}=-1$$

By plotting this transfer fucntion on the complex plane, you can gain insight into the current stability or stabilty for possible future orientations. A system whose transfer function has poles in the right-hand plane is always unstable. If the root locus lies on the imaginary axis and continues there for all time, the system is marginally stable. The system is stable if the poles lie in the left-hand plane or initally exist on the imaginary and continue to a "zero" point. The following figures are examples of root locus analysis for predicted ISS configurations.

The first is the plot for an always-stable orientation—configuration 19. K_y, K_r and the gain K are all positive. It is already stable for pitch.

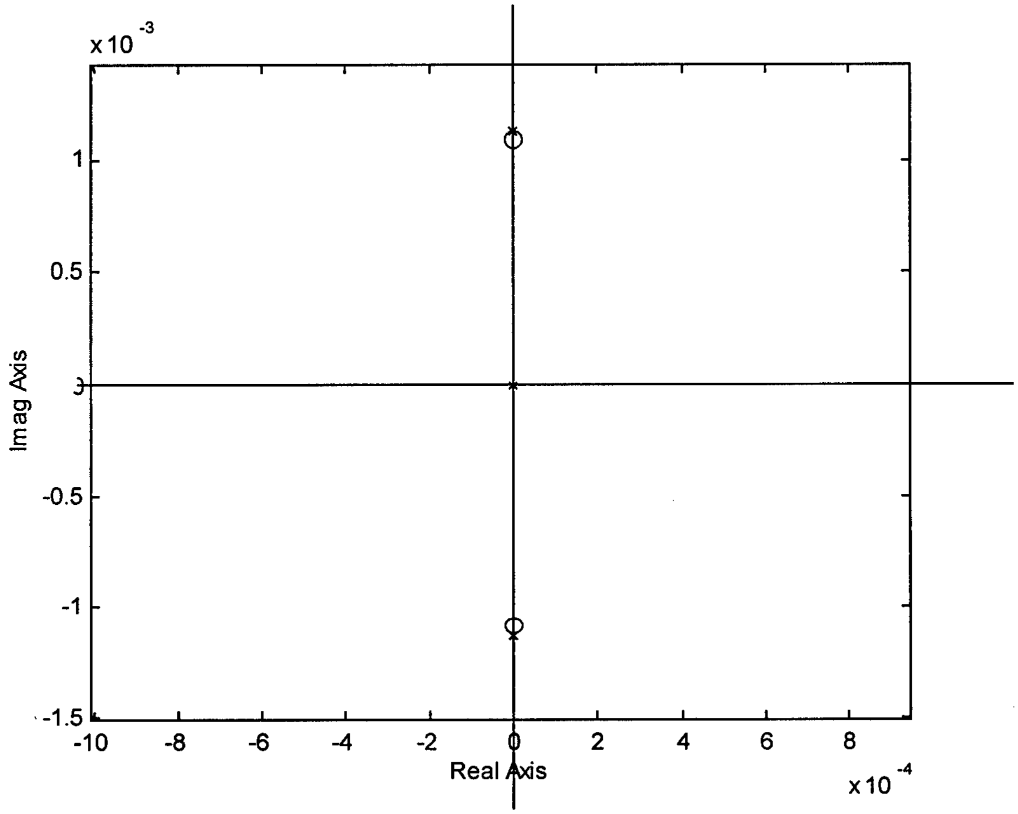


Figure 17: Root Locus for Configuration 19; K_Y,K_R,K>0

The next figure is an example of configuration 105. Though stable for pitch, the positive K_Y, and negative gain K cause the root locus to venture into the right-hand plane, making it always unstable.

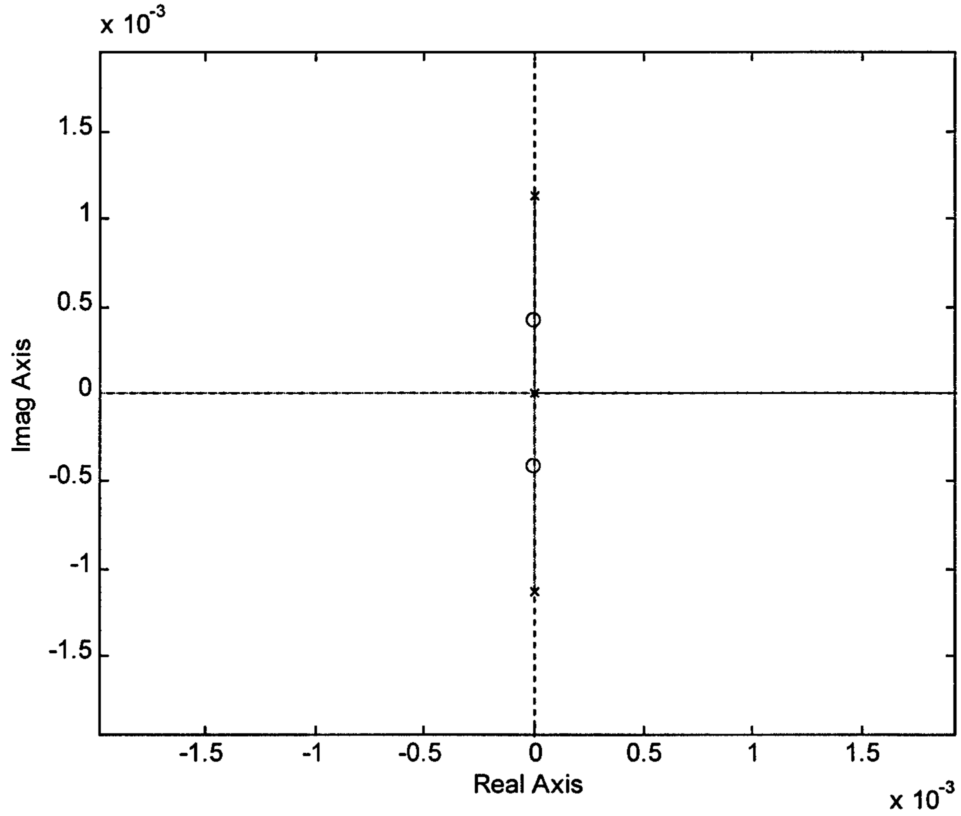


Figure 18: Root Locus for Configuration 105; K_Y>0; K_R, K<0

As you can see, the two poles on the imaginary axis (the y-axis) proceed to the zeros on the same axis. The poles at the origin proceed infinitetly into the right-hand and left-hand planes. Actual values of K_Y, K_R and K to produce these root locus plots can be found in the appendix.

CONCLUSION

The International Space Station will require concentration on many aspects of attitude control. First, extensive modeling must be conducted to study the multiple scenarios for all possible orientations before construction even begins. The work of Lockheed Martin's SEMDA Lab is promising in this regard, dealing with the various configurations during its ever-changing assembly process. Next, diligent monitoring of the Space Station's dynamics and attitude must be maintained throughout every moment of its construction and lifetime. Instability is not an option when dealing with decades of work from 15 countries. Finally, ground-based (or even space-based) modeling must continue throughout life-cycle operations in order to predict the affects of extra-vehicular activities (EVAs) and Shuttle rendezvous on the ISS's "temperamental" dynamic reactions. When completed in the year 2003, the International Space Station will represent humanity's greatest achievement beyond its own environment, and everyday of its operation will be a testament to the simple forces of kinematics, kinetics, and dynamics which have once bounded us to Earth.

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APPENDIX

List of Items

1. Gravity Gradient Stability *Excel* Spreadsheet
2. Mass Summary *Excel* Spreadsheet
   2.1 Mass Summary for Free-Flying Configurations (large)
   2.2 Mass-to-Orbit Summary per Flight (large)
3. *PowerPoint* Presentation

Jack Wojtowicz: Creative Investigation Spreadsheet omega^2= 1.276E-06 rad^2/sec^2

	Euler Angles (1,2,3 sequence)			Principal Moments of Inertia (kg*m^2)			Net Torques (kg*m^2/sec^2)		
Conf	Phi (roll)	Theta (pitch	Psi (yaw)	I1	I2	I3	Roll	Pitch	Yaw
1	-2.29	-0.38	-0.23	61011	173771	189849	0.00246	0.003271	-0.00011
2	0.11	27.12	-0.07	12875878	18075078	5753494	0.090544	12.90378	-0.01808
3	-1.6	2.67	-0.1	77979	1259725	1274509	0.00158	-0.213421	0.00589
4	-0.24	1.07	-0.1	217488	7788587	7890154	0.001628	-0.548444	0.00227
5	0.09	-26.13	-0.01	9871189	43173968	34108436	0.054505	42.3082	0.09131
6	0.1	-26.07	-0.02	9854323	43778480	34718544	0.060524	43.30298	0.10312
7	-0.55	1.1	-0.1	218314	7997527	8099922	0.003762	-0.579174	0.00549
8	0.15	-26.25	0	9761587	43913144	34961560	0.0897	44.19074	0.15679
9	0.11	-25.85	-0.02	9896291	43106948	34028196	0.066715	41.67293	0.11011
10	0.1	-25.97	-0.02	10009571	43165924	33974204	0.061404	41.57618	0.1004
11	42.38	-1.21	0.03	351392	10542248	10525531	0.047328	0.822403	0.60931
12	41.17	-1.41	0.04	34643	7301292	7284536	0.046084	0.682893	0.49183
13	42.46	-1.22	0.03	351291	10328115	10311422	0.04735	0.811758	0.60258
14	2.33	0.18	0.03	558691	1075513	10671711	-1.49368	-0.121606	-0.00025
15	0.37	9.54	-0.02	2601690	5262032	50870264	-1.12732	-30.76201	-0.01095
16	0.13	10.59	-0.01	6764474	55259624	49329224	0.051503	-30.11258	-0.07784
17	0.06	10.55	-0.04	7940804	55487168	50369892	0.020511	-29.90323	-0.03509
18	0.57	-13.77	-0.11	3149906	15540010	14754489	0.029911	10.67494	0.11339
19	0.46	-16.9	-0.15	3439110	12079977	11005215	0.033027	8.542027	0.07832
20	0.04	10.88	-0.02	8015821	57612856	52447508	0.013803	-32.29413	-0.02517
21	0.04	10.89	-0.02	8064507	57661016	52446984	0.013933	-32.28801	-0.02519
22	-0.29	10.43	-0.02	8123231	56358992	51164208	-0.10064	-29.98944	0.17011
23	-0.29	10.38	-0.02	8082567	56443948	51289828	-0.09985	-29.96098	0.16974
24	-0.71	-6.69	-0.14	3842411	19981324	18607888	-0.06514	6.59896	-0.08938
25	-0.63	-8.23	-0.14	4013366	20910404	19371768	-0.06476	8.443991	-0.10215
26	-0.62	-9.91	-0.18	3975378	16504622	14998263	-0.06239	7.297445	-0.08976

27	-0.63	-8.13	-0.14	4016343	21157580	19616016	-0.06488	8.472429	-0.10237
28	-0.13	24.59	0.02	17242434	76523376	62234568	-0.12409	-73.90894	0.22095
29	-0.08	24.28	0.01	17257568	74939888	60657184	-0.07633	-70.39413	0.13064
30	-0.07	24.52	0.01	17528508	74733304	60184360	-0.06803	-69.87164	0.11448
31	0.02	24.55	0.02	17425040	75894624	61479504	0.01926	-72.2509	-0.03347
32	-1.54	-6.99	0.17	4130585	22522554	20921636	-0.1647	7.840738	-0.23084
33	0.03	24.7	0.01	17452004	76732104	62298424	0.028927	-73.99913	-0.05122
34	-0.41	24.52	0.16	17510212	75024136	60791804	-0.38982	-70.89663	0.67415
35	2.45	-6.13	-0.68	4389115	23277986	21678556	0.261778	7.080164	0.33076
36	-0.41	24.63	0.17	17625956	76355576	62011556	-0.39288	-73.03119	0.69149
37	-0.41	24.64	0.17	17615900	76358648	62024680	-0.3926	-73.099	0.69192
38	2.45	-6.13	-0.68	4389190	23279220	21679722	0.261789	7.08061	0.33078
39	1.86	-6	-0.68	4622048	23517624	21693848	0.226614	6.842778	0.24587
40	2.12	-4.82	-0.65	4471428	22427506	20747772	0.237891	5.240899	0.21393
41	2.03	-5.3	-0.67	4512352	23002868	21284660	0.23301	5.938415	0.23195
42	-0.4	25.25	0.18	17441912	76218512	62066960	-0.37815	-75.27347	0.69216
43	-0.37	25.35	0.18	17842404	75982112	61436500	-0.35953	-73.82569	0.63582
44	1.83	-5.14	-0.57	4735347	24154212	22222340	0.236174	6.004545	0.21297
45	-0.36	25.31	0.18	17884518	76706376	62124640	-0.35068	-74.8015	0.6249
46	-0.32	25.45	0.17	18990828	75173280	59790096	-0.32885	-69.36526	0.53348
47	2.14	-5.87	-0.45	4963285	26221354	24394244	0.261204	7.619636	0.31135
48	-0.32	25.78	0.19	19089724	77391608	61929916	-0.33053	-73.77958	0.56078
49	-0.2	25.85	0.18	19329842	76832272	61171000	-0.20925	-72.2547	0.34662
50	2.64	-5.95	-0.34	5021129	26742412	24903988	0.324229	7.903104	0.39782
51	2.78	-5.9	-0.39	5039797	26764532	24882776	0.34947	7.820972	0.41546
52	2.09	-8.03	-0.41	5490823	28548258	26224036	0.324508	11.12203	0.45118
53	2.51	-7.94	-0.41	5270695	28325480	26213184	0.354185	11.10838	0.53572
54	-0.25	23.8	0.19	20452884	81058976	64269296	-0.2804	-69.66516	0.42045
55	-6.13	23.82	0.37	23919096	79492480	64100580	-6.30311	-63.93955	9.46125
56	20.96	-8.35	-5.45	7611609	30280624	30507048	-0.31704	12.77137	4.62583

57	-6.18	24.21	0.56	24101218	82905360	67356360	-6.41938	-69.95752	10.2582
58	-5.86	24.86	0.07	24134558	87991880	72431424	-6.09147	-80.20879	10.8465
59	-4.89	-5.18	-5.46	8591202	33530140	32717358	-0.26551	8.348717	-0.73654
60	-0.7	-3.78	-5.8	10427549	34895516	33304764	-0.07439	5.776926	-0.07549
61	-5.64	26.29	0.06	25524716	93076680	77276808	-5.95298	-90.89089	11.6785
62	-0.04	26.09	-0.06	29165312	90431568	77153616	-0.03548	-83.63949	0.07455
63	-5.85	-4.12	-0.66	13751270	36429120	38132104	0.665531	6.710388	-0.63729
64	-6.89	-4.25	-0.66	14063858	36748316	38149664	0.645011	6.83836	-0.77449
65	-4.58	-1.94	-0.68	13366033	34702120	36781688	0.636269	3.034659	-0.22104
66	-8.59	-4.57	-0.65	1421032	38247192	39378952	0.649455	11.58832	-1.68556
67	-0.11	25.58	-0.03	29947224	97755280	83604176	-0.10399	-91.69136	0.22246
68	33.86	24.47	0.27	43135692	97429168	90773816	15.05428	-77.87364	-52.4503
69	-0.81	-4.65	14.97	25384166	42083256	54215256	0.656477	8.956037	-0.07333
70	-1.42	-1.97	15.96	24441728	38929988	51938768	1.234033	3.618712	-0.04726
71	0.03	-8.28	14.32	26947984	45618352	56250008	-0.02131	16.20801	0.00541
72	0.01	-9.83	14.35	27473432	47373432	57483884	-0.00675	19.70734	0.00228
73	1.06	-9.79	13.73	27057040	47332696	57024696	-0.68631	19.59915	0.24533
74	21.37	21.37	0.62	46895856	107549520	97913840	13.75589	-72.83325	-32.2957
75	3.01	20.19	-0.04	61122504	102838520	108879008	-1.21462	-64.41258	-2.95587
76	-0.79	-10.06	-4.4	42002216	48172056	72763440	1.297812	20.673	-0.05717
77	-1.17	-9.51	-2.47	41643768	48989868	73036664	1.879511	19.94407	-0.0953
78	-0.56	21.11	-0.17	60934648	108430800	113692952	0.196858	-74.40137	0.65466
79	-1.75	19.96	-0.3	61199008	104186160	110215000	0.704813	-65.35822	1.75072
80	0.04	-9.12	1	42328288	49521804	73939376	-0.06525	19.25911	0.00306
81	-0.88	-7.03	-1.27	42056508	55032328	78699072	1.391307	17.2085	-0.09359
82	-0.97	-9.84	-1.12	43749800	58671616	80653112	1.424396	24.25841	-0.16606
83	-0.97	-9.71	-1.11	43564128	58442444	80603904	1.436058	24.02644	-0.16339
84	-1.26	17.03	-0.04	62256888	139146288	143116352	0.334172	-91.99143	1.92367
85	-7.66	14.26	-0.68	92076968	132330608	172694208	20.65478	-76.7979	5.12664
86	-4.83	-6.25	-23.57	75779752	58597860	117811088	19.10591	17.54911	0.60475

87	-4.84	-6.25	-23.7	75814040	58562448	117827200	19.16213	17.54152	0.60846
88	-4.87	-3.88	-34.02	80282008	60631736	123803672	20.55204	11.28078	0.43292
89	-4.87	-3.68	-35.33	80832472	61087164	124779872	20.72147	10.80396	0.41259
90	-2.73	-3.33	-26.12	80762160	60839696	127091728	12.08269	10.30634	0.21117
91	-2.29	-2.95	-27.71	84806648	62017220	131990408	10.70456	9.298576	0.1795
92	-3.49	-4.69	-30.7	87361576	65128784	134305856	16.12833	14.70813	0.4243
93	-2.4	-3.09	-27.48	85116744	62147136	131765240	11.16183	9.629373	0.19861
94	-3.25	-3.49	-30.78	91996856	68226696	137763488	15.09732	10.67029	0.31435
95	-2.88	-3.84	-29.63	93439376	69325784	140149936	13.62623	11.98252	0.31093
96	-3.06	-3.37	-29.43	94649760	70619712	140331584	14.2505	10.28431	0.28893
97	-2.93	-2.53	-28.25	94975432	70134304	139371984	13.55227	7.503634	0.2147
98	-2.95	-2.42	-28.84	95185984	70676872	140091744	13.6797	7.25971	0.20401
99	-3.69	-3.11	-32.46	96213040	76409120	146400096	17.25323	10.42687	0.26498
100	-3.32	-2.62	-30.64	96083152	76202248	145267024	15.31781	8.608468	0.20163
101	-3.34	-2.99	-27.35	94937616	75147728	142978240	15.13469	9.595811	0.23043
102	-4.05	-3.94	-29.42	96377720	76983488	144405920	18.24153	12.64138	0.36083
103	-4.08	-3.87	-29.87	96511744	77286280	144825504	18.40849	12.49061	0.35394
104	-4.43	-4.63	-33.03	96751976	79938568	147739248	20.06502	15.77047	0.40209
105	1.44	-4.95	38	86987344	104000112	160516448	-5.43674	24.31456	0.14139
106	2.72	-5.78	38.42	89255280	105567928	164683264	-10.7416	29.12475	0.29902
107	-0.08	-8.09	-3.57	123486912	89337968	182705824	0.498987	32.00448	0.02577
108	-0.19	-8.02	-4.47	123829888	90408416	184063984	1.188746	32.27146	0.05938
109	-0.02	-8.05	-3.75	125674400	90517824	186001472	0.127574	32.44218	0.0066
110	0.06	-7.99	-3.75	128330496	94737952	187182912	-0.37054	31.41326	-0.01878
111	-1.12	10.03	8.3	146033248	157105120	232611664	5.649428	-58.01128	0.14502
112	0.37	-7.25	-3.26	126577648	92351144	187531744	-2.35262	29.5218	-0.10705

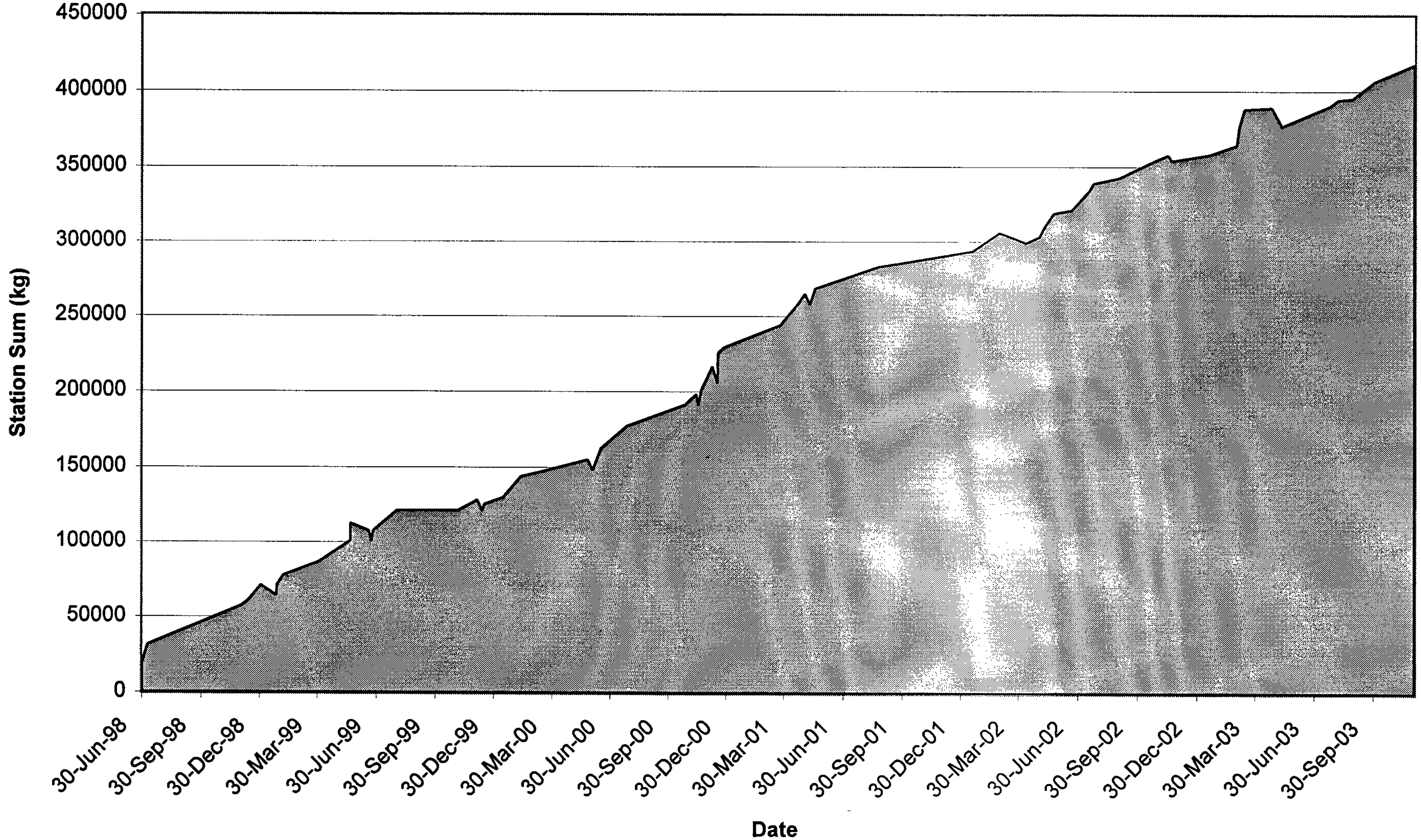
Conf	(within 5%) Antisym	Axisym	Sym	Stable for Pitch?	Ky	Kr	K	Stability in Roll/Yaw
1	I1<I2<I3			YES	0.59394571	-0.2635262	-1.2E-06	Always Unstable!
2	I3<I1<I2			YES	0.90365958	0.956951	4.77E-06	Always Stable!
3		I2=I3>I1		NO	0.92721668	0	0	Always Marginally Stable
4		I2=I3>I1		NO	0.95956289	0	0	Always Marginally Stable
5	I1<I3<I2			YES	0.97637954	0.918383	4.66E-06	Always Stable!
6	I1<I3<I2			YES	0.97711923	0.919387	4.67E-06	Always Stable!
7		I2=I3>I1		NO	0.96040592	0	0	Always Marginally Stable
8	I1<I3<I2			YES	0.97683161	0.9170214	4.65E-06	Always Stable!
9	I1<I3<I2			YES	0.97597466	0.9173894	4.65E-06	Always Stable!
10	I1<I3<I2			YES	0.97592729	0.9182931	4.66E-06	Always Stable!
11		I2=I3>I1		YES	0.9682035	0	0	Always Marginally Stable
12		I2=I3>I1		YES	0.99754452	0	0	Always Marginally Stable
13		I2=I3>I1		YES	0.96755074	0	0	Always Marginally Stable
14	I1<I2<I3			NO	0.04842916	-17.176217	-6.7E-05	Always Unstable!
15	I1<I2<I3			NO	0.0522966	-17.530233	-6.8E-05	Always Unstable!
16	I1<I3<I2			NO	0.98309169	0.8766979	4.46E-06	Always Stable!
17	I1<I3<I2			NO	0.94394413	0.6444279	3.24E-06	Always Stable!
18	I1<I3<I2			YES	0.83975148	0.2493792	1.22E-06	Always Stable!
19	I1<I3<I2			YES	0.78516113	0.3125117	1.51E-06	Always Stable!
20	I1<I3<I2			NO	0.94565094	0.6443941	3.24E-06	Always Stable!
21	I1<I3<I2			NO	0.94565035	0.6465407	3.25E-06	Always Stable!
22	I1<I3<I2			NO	0.94276376	0.6394973	3.22E-06	Always Stable!
23	I1<I3<I2			NO	0.94290394	0.6376835	3.21E-06	Always Stable!
24	I1<I3<I2			YES	0.86731568	0.3574412	1.76E-06	Always Stable!
25	I1<I3<I2			YES	0.87225069	0.3833779	1.89E-06	Always Stable!
26	I1<I3<I2			YES	0.83537967	0.3789222	1.85E-06	Always Stable!
27	I1<I3<I2			YES	0.87383886	0.3838228	1.9E-06	Always Stable!

28	I1<I3<I2		NO	0.95254043	0.8287002	4.18E-06	Always Stable!
29	I1<I3<I2		NO	0.95095611	0.8276197	4.17E-06	Always Stable!
30	I1<I3<I2		NO	0.95049272	0.8300161	4.18E-06	Always Stable!
31	I1<I3<I2		NO	0.9510419	0.8272647	4.17E-06	Always Stable!
32	I1<I3<I2		YES	0.87908847	0.3875766	1.92E-06	Always Stable!
33	I1<I3<I2		NO	0.95155056	0.82705	4.17E-06	Always Stable!
34	I1<I3<I2		NO	0.94608023	0.8128018	4.09E-06	Always Stable!
35	I1<I3<I2		YES	0.87131592	0.3644083	1.8E-06	Always Stable!
36	I1<I3<I2		NO	0.94707541	0.813801	4.1E-06	Always Stable!
37	I1<I3<I2		NO	0.94708668	0.8136949	4.1E-06	Always Stable!
38	I1<I3<I2		YES	0.87132252	0.3644176	1.8E-06	Always Stable!
39	I1<I3<I2		YES	0.8710108	0.3945818	1.95E-06	Always Stable!
40	I1<I3<I2		YES	0.86544608	0.3756594	1.85E-06	Always Stable!
41	I1<I3<I2		YES	0.86872499	0.3807788	1.88E-06	Always Stable!
42	I1<I3<I2		NO	0.94698693	0.8113533	4.09E-06	Always Stable!
43	I1<I3<I2		NO	0.94633822	0.8152271	4.1E-06	Always Stable!
44	I1<I3<I2		YES	0.87384429	0.4079684	2.02E-06	Always Stable!
45	I1<I3<I2		NO	0.9468362	0.8153273	4.11E-06	Always Stable!
46	I1<I3<I2		NO	0.93966151	0.8100323	4.07E-06	Always Stable!
47	I1<I3<I2		YES	0.87143791	0.3681251	1.82E-06	Always Stable!
48	I1<I3<I2		NO	0.94141713	0.8099484	4.07E-06	Always Stable!
49	I1<I3<I2		NO	0.94002763	0.8102121	4.07E-06	Always Stable!
50	I1<I3<I2		YES	0.87220099	0.3661376	1.81E-06	Always Stable!
51	I1<I3<I2		YES	0.87308325	0.3733793	1.85E-06	Always Stable!
52	I1<I3<I2		YES	0.87924814	0.4232921	2.1E-06	Always Stable!
53	I1<I3<I2		YES	0.87951105	0.4007623	1.98E-06	Always Stable!
54	I1<I3<I2		NO	0.94300227	0.8208955	4.13E-06	Always Stable!
55	I1<I3<I2		NO	0.86697162	0.6434984	3.17E-06	Always Stable!
56		I2=I3>I1	YES	0.74307468	0	0	Always Marginally Stable
57	I1<I3<I2		NO	0.87303028	0.6451541	3.19E-06	Always Stable!

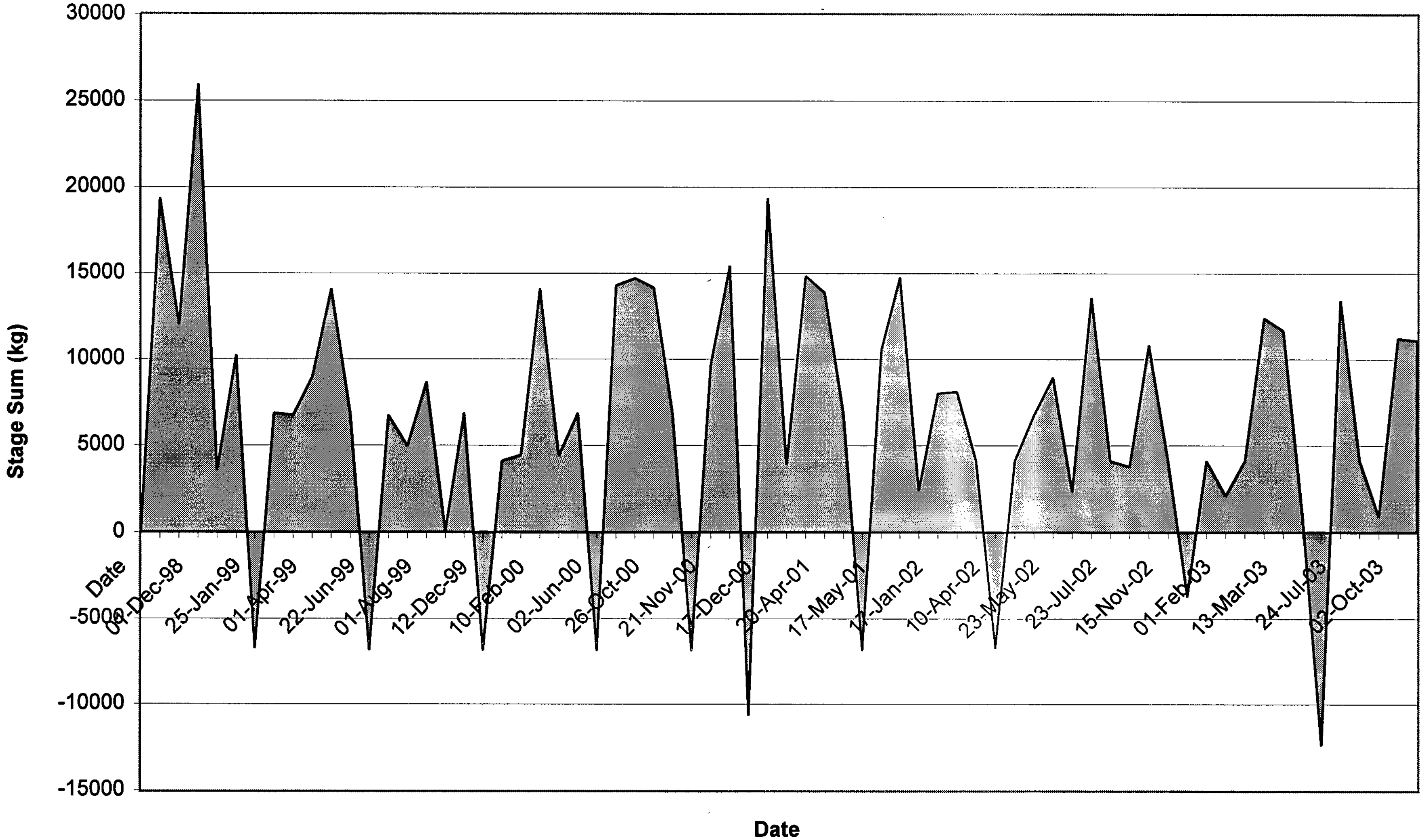
58	I1<I3<I2		NO	0.88162456	0.6447376	3.19E-06	Always Stable!
59		I2=I3>I1	YES	0.76225403	0	0	Always Marginally Stable
60		I2=I3>I1	YES	0.73466868	0	0	Always Marginally Stable
61	I1<I3<I2		NO	0.87415572	0.6190029	3.06E-06	Always Stable!
62	I1<I3<I2		NO	0.79408146	0.4552652	2.2E-06	Always Stable!
63		I2=I3>I1	YES	0.59471804	0	0	Always Marginally Stable
64		I2=I3>I1	YES	0.5946175	0	0	Always Marginally Stable
65	I1<I2<I3		YES	0.58007362	-0.155586	-7.1E-07	Always Unstable!
66		I2=I3>I1	YES	0.93517369	0	0	Always Marginally Stable
67	I1<I3<I2		NO	0.81106063	0.4725347	2.3E-06	Always Stable!
68	I1<I3<I2		NO	0.59811825	0.1542888	7.08E-07	Always Stable!
69	I1<I2<I3		YES	0.30801459	-0.4779357	-2E-06	Always Unstable!
70	I1<I2<I3		YES	0.27894886	-0.5322365	-2.2E-06	Always Unstable!
71	I1<I2<I3		YES	0.33191761	-0.3945251	-1.7E-06	Always Unstable!
72	I1<I2<I3		YES	0.34618398	-0.3680083	-1.6E-06	Always Unstable!
73	I1<I2<I3		YES	0.35555921	-0.3582062	-1.5E-06	Always Unstable!
74	I1<I3<I2		NO	0.61945956	0.2054698	9.49E-07	Always Stable!
75	I1<I2<I3		NO	0.38314104	-0.0988259	-4.3E-07	Always Unstable!
76	I1<I2<I3		YES	0.08479313	-0.5854783	-2.3E-06	Always Unstable!
77	I1<I2<I3		YES	0.10058099	-0.5774404	-2.3E-06	Always Unstable!
78		I2=I3>I1	NO	0.4177581	0	0	Always Marginally Stable
79	I1<I2<I3		NO	0.39002996	-0.0985121	-4.3E-07	Always Unstable!
80	I1<I2<I3		YES	0.09728938	-0.5768618	-2.3E-06	Always Unstable!
81	I1<I2<I3		YES	0.16487895	-0.5627368	-2.3E-06	Always Unstable!
82	I1<I2<I3		YES	0.18501228	-0.5024365	-2E-06	Always Unstable!
83	I1<I2<I3		YES	0.18458555	-0.5087089	-2.1E-06	Always Unstable!
84		I2=I3>I1	NO	0.53725098	0	0	Always Marginally Stable
85	I1<I2<I3		NO	0.23309201	-0.438368	-1.8E-06	Always Unstable!
86	I2<I1<I3		YES	-0.1458427	-0.7813859	-2.8E-06	Marginally stable for small K, then Unstable
87	I2<I1<I3		YES	-0.1464143	-0.7817121	-2.8E-06	Marginally stable for small K, then Unstable

88	I2<I1<I3	YES	-0.1587212	-0.7868754	-2.9E-06	Marginally stable for small K, then Unstable
89	I2<I1<I3	YES	-0.1582411	-0.7879594	-2.9E-06	Marginally stable for small K, then Unstable
90	I2<I1<I3	YES	-0.1567566	-0.8203351	-3E-06	Marginally stable for small K, then Unstable
91	I2<I1<I3	YES	-0.1726597	-0.8250908	-3E-06	Marginally stable for small K, then Unstable
92	I2<I1<I3	YES	-0.1655385	-0.7918478	-2.9E-06	Marginally stable for small K, then Unstable
93	I2<I1<I3	YES	-0.1743222	-0.8179131	-2.9E-06	Marginally stable for small K, then Unstable
94	I2<I1<I3	YES	-0.1725433	-0.7558605	-2.7E-06	Marginally stable for small K, then Unstable
95	I2<I1<I3	YES	-0.1720557	-0.757969	-2.7E-06	Marginally stable for small K, then Unstable
96	I2<I1<I3	YES	-0.1712376	-0.7365246	-2.7E-06	Marginally stable for small K, then Unstable
97	I2<I1<I3	YES	-0.1782362	-0.7290062	-2.6E-06	Marginally stable for small K, then Unstable
98	I2<I1<I3	YES	-0.1749504	-0.7292552	-2.6E-06	Marginally stable for small K, then Unstable
99	I2<I1<I3	YES	-0.1352726	-0.7274583	-2.7E-06	Marginally stable for small K, then Unstable
100	I2<I1<I3	YES	-0.1368577	-0.7188021	-2.6E-06	Marginally stable for small K, then Unstable
101	I2<I1<I3	YES	-0.1384119	-0.7144746	-2.6E-06	Marginally stable for small K, then Unstable
102	I2<I1<I3	YES	-0.1343036	-0.6995645	-2.6E-06	Marginally stable for small K, then Unstable
103	I2<I1<I3	YES	-0.1327492	-0.6998032	-2.6E-06	Marginally stable for small K, then Unstable
104	I2<I1<I3	YES	-0.1138046	-0.7007679	-2.6E-06	Marginally stable for small K, then Unstable
105	I1<I2<I3	YES	0.10598769	-0.6497076	-2.6E-06	Always Unstable!
106	I1<I2<I3	YES	0.09905468	-0.6623175	-2.6E-06	Always Unstable!
107	I2<I1<I3	YES	-0.1869067	-0.7560952	-2.7E-06	Marginally stable for small K, then Unstable
108	I2<I1<I3	YES	-0.1815753	-0.7563244	-2.7E-06	Marginally stable for small K, then Unstable
109	I2<I1<I3	YES	-0.1890124	-0.7597701	-2.7E-06	Marginally stable for small K, then Unstable
110	I2<I1<I3	YES	-0.1794637	-0.7203663	-2.6E-06	Marginally stable for small K, then Unstable
111	I1<I2<I3	NO	0.04759809	-0.5170504	-2E-06	Always Unstable!
112	I2<I1<I3	YES	-0.1825105	-0.7519542	-2.7E-06	Marginally stable for small K, then Unstable

Mass Summary for Free Flying Configurations



Mass-to-Orbit Summary per Flight

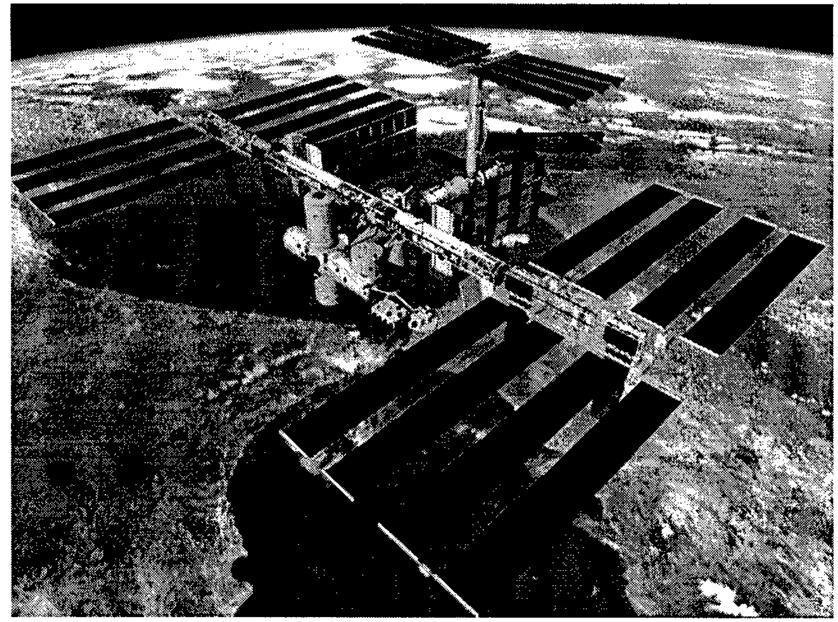


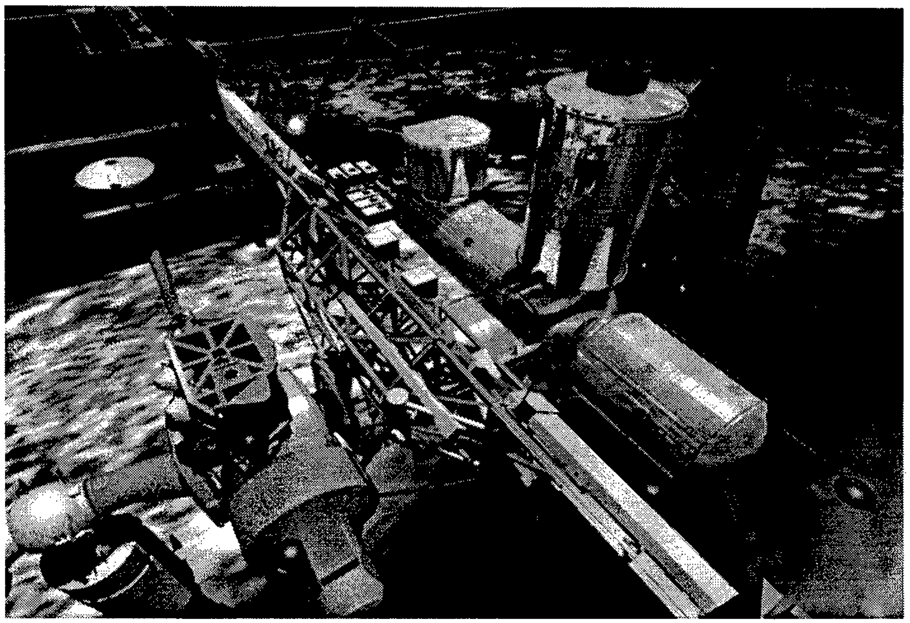
Mass Summary for Free Flight Configruations

Date	Net Sum	Station Sum
30-Jun-98	19340	19340
09-Jul-98	11991	31331
01-Dec-98	25913	57244
12-Dec-98	3570	60814
01-Jan-99	10220	71034
25-Jan-99	-6733	64301
26-Jan-99	6850	71151
05-Feb-99	6733	77884
01-Apr-99	8918	86802
20-May-99	14084	100886
18-Jun-99	6850	107736
22-Jun-99	-6850	100886
25-Jun-99	6733	107619
20-May-99	4950	112569
01-Aug-99	8663	121232
04-Nov-99	73	121305
04-Dec-99	6850	128155
12-Dec-99	-6850	121305
15-Dec-99	4100	125405
13-Jan-00	4441	129846
10-Feb-00	14102	143948
24-Mar-00	4407	148355
25-May-00	6850	155205
02-Jun-00	-6850	148355
15-Jun-00	14290	162645
26-Jul-00	14700	177345
26-Oct-00	14155	191500
13-Nov-00	6850	198350
16-Nov-00	-6850	191500
21-Nov-00	9680	201180
08-Dec-00	15423	216603
16-Dec-00	-10633	205970
17-Dec-00	19340	225310
26-Dec-00	3900	229210
24-Mar-01	14833	244043
20-Apr-01	13878	257921
01-May-01	6850	264771
09-May-01	-6850	257921
17-May-01	10514	268435
23-Aug-01	14768	283203
27-Sep-01	2404	285607
17-Jan-02	8011	293618
14-Feb-02	8120	301738
28-Feb-02	4100	305838
10-Apr-02	-6733	299105
01-May-02	4100	303205

09-May-02	6733	309938
23-May-02	8939	318877
20-Jun-02	2328	321205
18-Jul-02	13568	334773
23-Jul-02	4100	338873
01-Sep-02	3772	342645
24-Oct-02	10815	353460
15-Nov-02	4100	357560
21-Nov-02	-3723	353837
18-Jan-03	4100	357937
01-Feb-03	2095	360032
01-Mar-03	4100	364132
05-Mar-03	12367	376499
13-Mar-03	11648	388147
24-Apr-03	944	389091
10-May-03	-12367	376724
24-Jul-03	13398	390122
06-Aug-03	4111	394233
28-Aug-03	883	395116
02-Oct-03	11205	406321
03-Dec-03	11062	417383

Dynamics of the International Space Station Throughout the Assembly Sequence





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Masters of Engineering

University of Colorado,
Colorado Springs

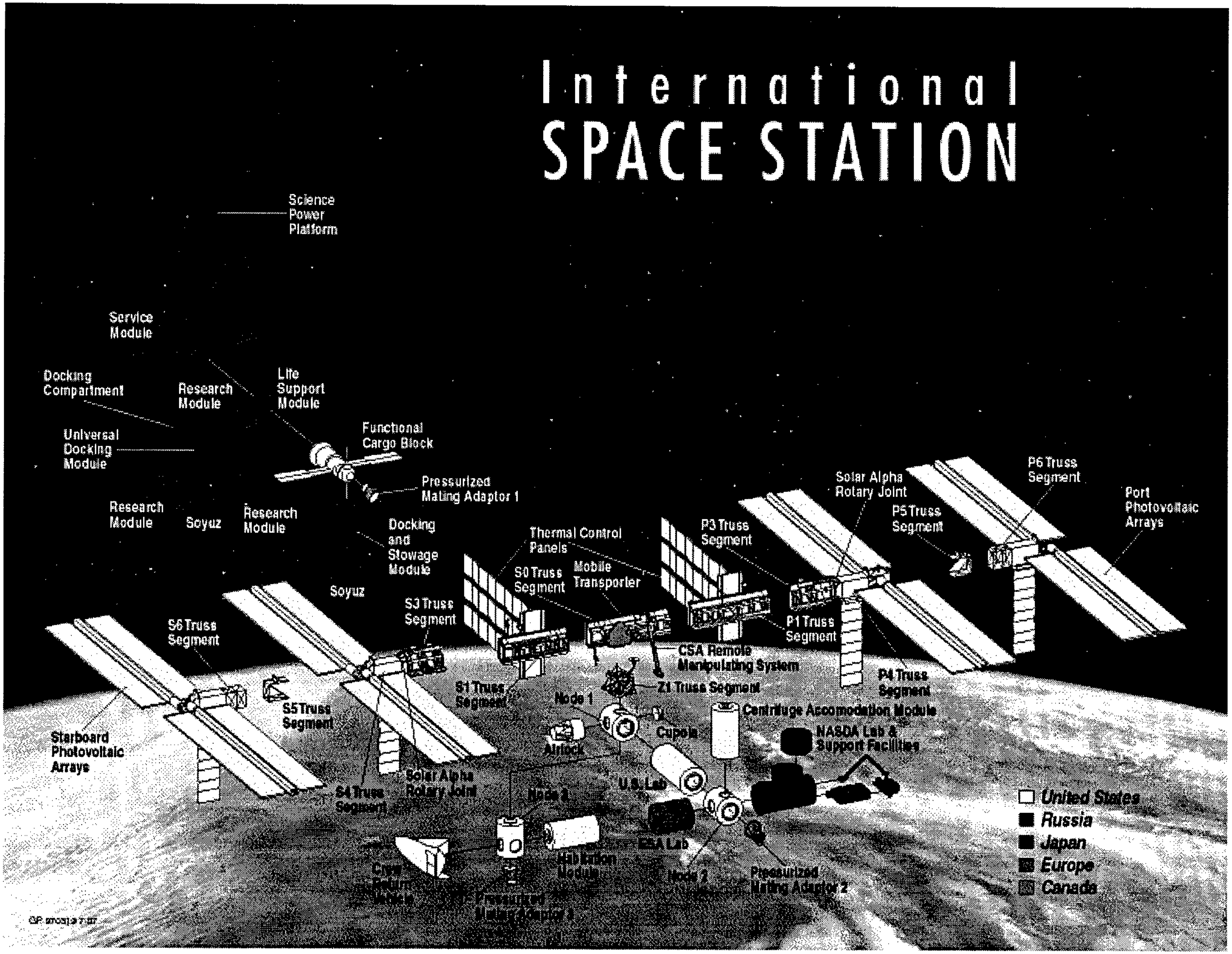
30 April 1998

Overview

- Introduction into station goals, past,present and future
- Background into ISS construction
- Assembly Process
- Coordinate Systems
- Major Players
- Mass Property Analysis
- Gravity Gradient Stability
- Conclusion

Introduction

- NASA's goals
  - Expand US leadership of the global community
  - Forge new partnerships
  - Driving force for emerging technologies
  - Encourage education
  - Satisfy humanity's need to explore
- ISS facts:
  - 950,000 pounds
  - 290 ft long, spans 356 ft
  - Orbits at 400km, 51.6°



International
SPACE STATION
Science Power Platform
Service Module
Docking Compartment
Research Module
Life Support Module
Universal Docking Module
Functional Cargo Block
Pressurized Mating Adaptor 1
Research Module
Soyuz
Research Module
Docking and Stowage Module
Soyuz
Thermal Control Panels
S0 Truss Segment
Mobile Transporter
P3 Truss Segment
Solar Alpha Rotary Joint
P5 Truss Segment
P6 Truss Segment
Port Photovoltaic Arrays
S6 Truss Segment
S3 Truss Segment
P1 Truss Segment
CSA Remote Manipulating System
P4 Truss Segment
Z1 Truss Segment
S1 Truss Segment
S5 Truss Segment
Node 1
Centrifuge Accomodation Module
Starboard Photovoltaic Arrays
Cupola
Airlock
NASDA Lab & Support Facilities
S4 Truss Segment
Solar Alpha Rotary Joint
Node 3
U.S. Lab
United States
Russia
Japan
Europe
Canada
ESA Lab
Habitation Module
Node 2
Pressurized Mating Adaptor 2
Crew Return Vehicle
Pressurized Mating Adaptor 3

“Bigger than a Breadbox?”

Parameter	Skylab	Space Shuttle	Mir	ISS
Total Volume (m^3)	354	166	410	1,120
Total Modules	2	2	9	17
Total Mass (kg)	90,000	123,700	140,000	419,000
Launches to Assemble	1	N/A	6	45
Solar Array Area (m^2)	165	0	430	~3,000
Total Power (kW)	18	7.7	<25	110
Docking Sites	1	1	4	6
Steady State Acceleration (g $x10^{-6}$)	(never recorded)	1-10	50-250	1 (requirement)

Background

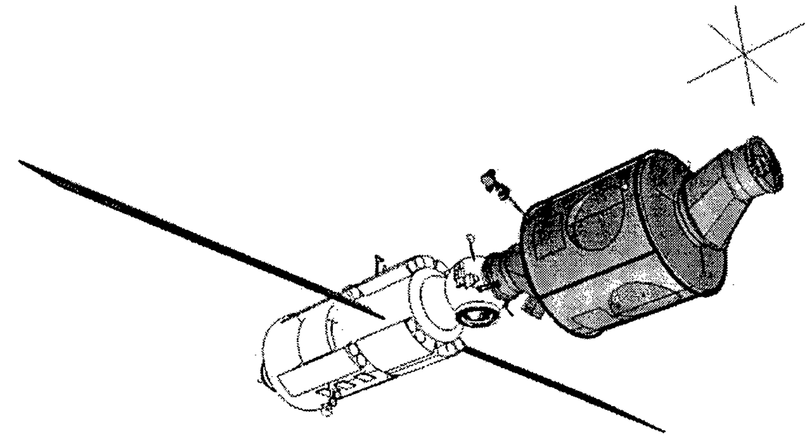
- Phase I
  - Includes stay by US astronauts on Mir
  - Valuable experience in Shuttle/Station dockings, crew rotations and repair
- Phase II
  - Begins with launch of Functional Cargo Block (FGB) on June 30th.
  - Forms core of station
  - Support human presence, microgravity - Aug 99
- Phase III
  - ISS construction completed - Dec 03

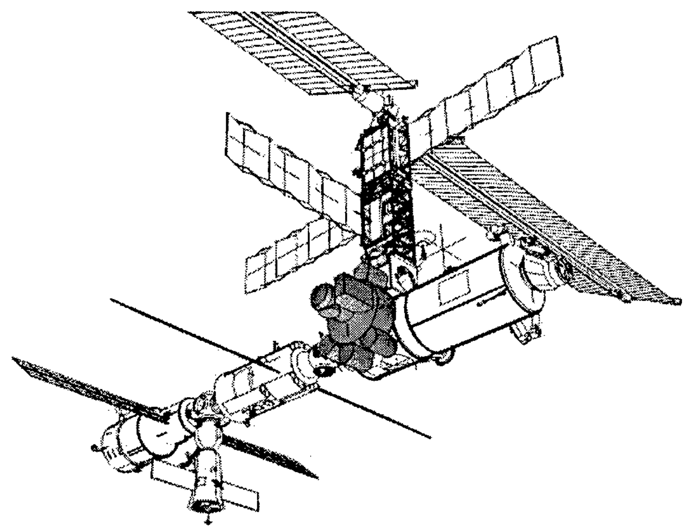
Assembly Sequence

- Representatives of all 15 nations signed agreement in Houston Oct ‘97 which finalized sequence
- Latest revision: Rev. C
- 45 flights
- Currently on target

Assembly Sequence

Stage 2A ⇒
09 July 98
First US hardware, Node 1, docks with already-orbiting FGB

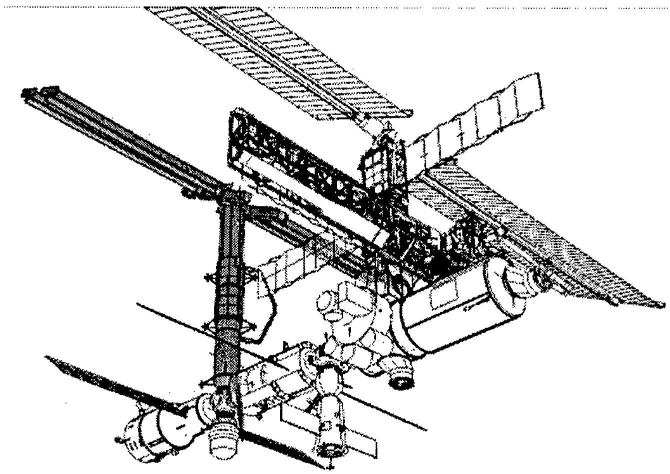


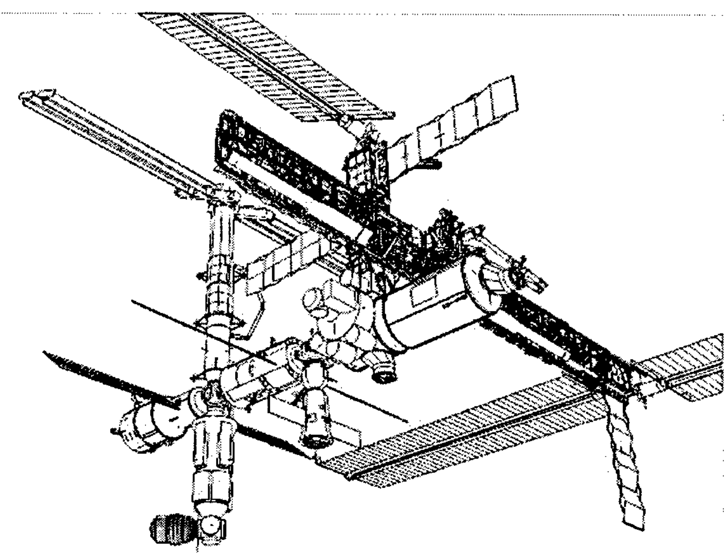


⇐ Stage 7A
12 August 99
Phase II Complete
Initial Science/Microgravity Capability

Assembly Sequence

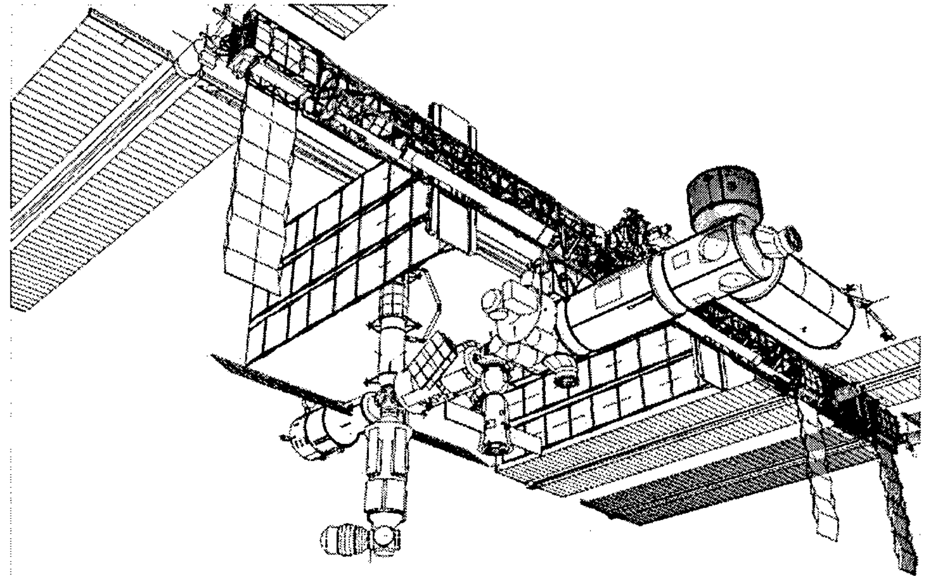
Stage 9A.1 ⇒
20 July 2000
STS-109 delivers Science Power Platform, European Robotic Arm



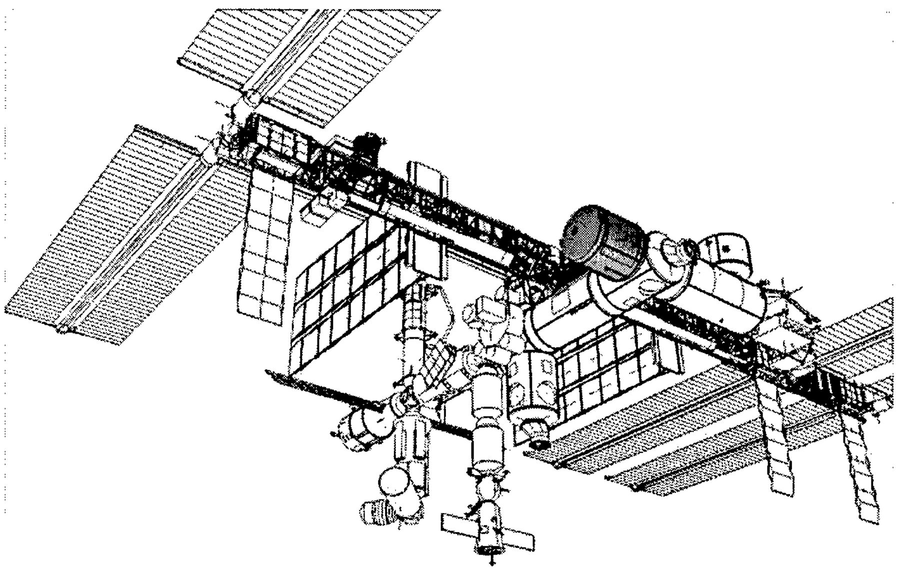


⇐ Stage 5R
26 December 2000
Docking Compartment #2 docks to UDM and replaces discarded DC#1

Assembly Sequence

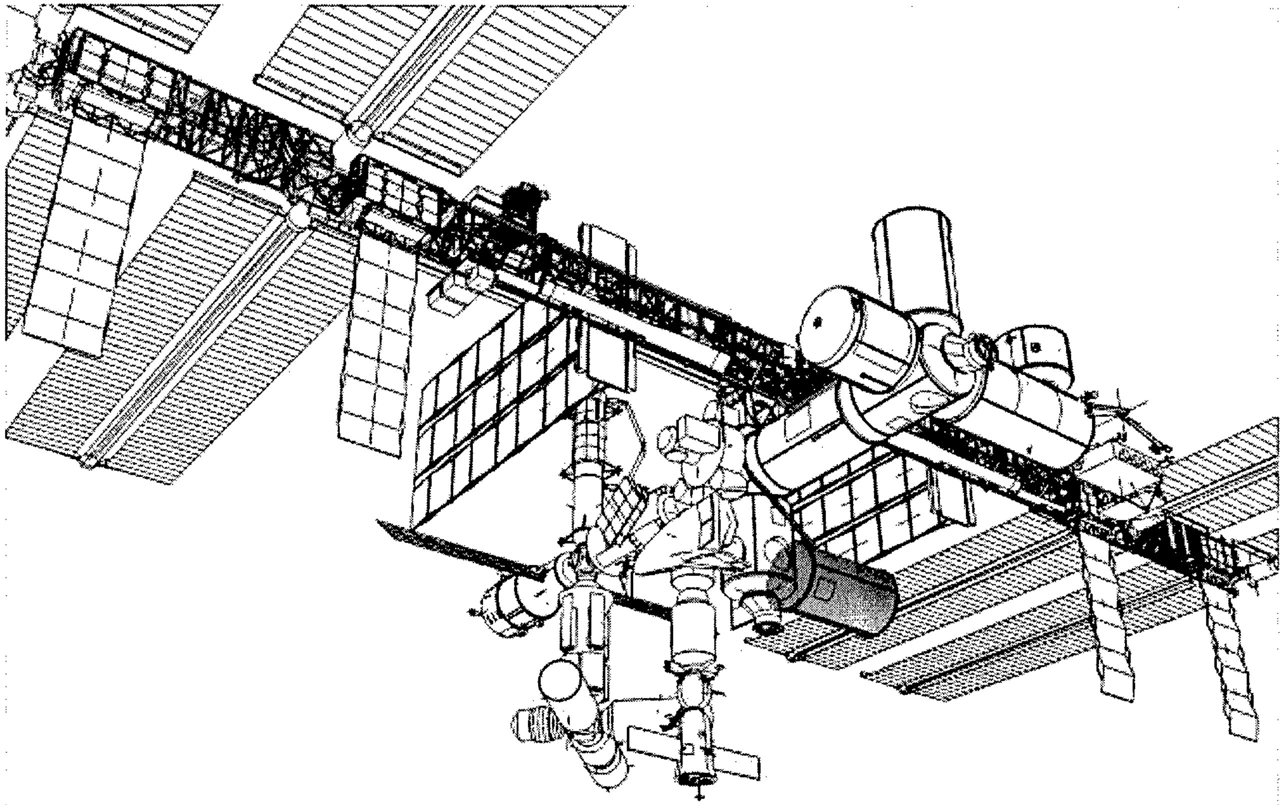


Stage 1J/A ⇒
10 May 2001
Japanese Experimentation Module (JEM)
Integrated Truss Structure Port-5 Array (ITS P5)



⇐ Stage 1E
24 October 2002
US Orbiter (STS-129) delivers ESA's Columbus Orbital Facility

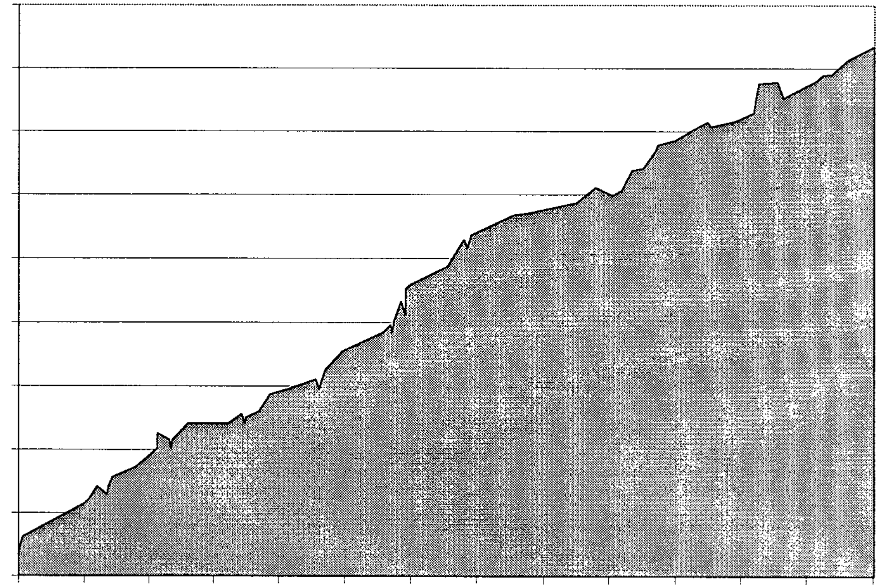
Assembly Complete

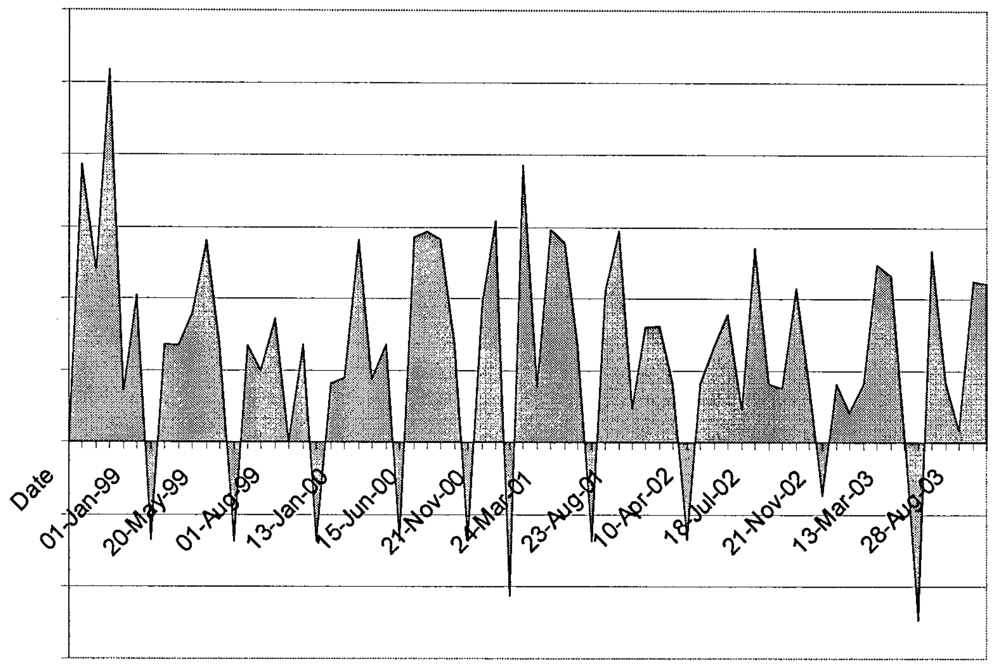


Stage 16A
04 December 2003

STS-126 delivers US Habitation Module to enhance crew accommodations and complete Phase III of construction

Mass of Free-Flying Configurations ⇒





⇐ Net Mass-to-Orbit

Coordinate Systems

Coordinate System	Reference Frame	Origin	Rationale/Use
Local Vertical-Local Horizontal (LVLH)	X_{LO}, Y_{LO}, Z_{LO}	Center of vehicle mass	Astrodynamics
Space Station Analysis System	X_A, Y_A, Z_A	Center of ITS S0 truss	Primary coordinate system (U.S.);Nose, Right Wing, Down (NRD)
Orbiter Structural System	X_0, Y_0, Z_0	236 in. beyond nose/400 in. below bay centerline	Mated manuevers; combining Shuttle/Station properties
Principal Axes	P1, P2, P3	Center of mass	Simplify body dynamics
RSA Analysis System	X_R, Y_R, Z_R	FGB/Service Module connection	Early construction

Integrated Prime Contractor

BOEING

- Boeing chosen as the Integrated Prime Contractor for the ISS
- Responsible for design, development, testing, verification, and delivery of all U.S. hardware and FGB
- Exercises direct management of Flight Elements & Subsystems, as well as on-orbit performance throughout assembly and life-cycle operation
- *"When you consider all the people, all the manufacturing facilities, all around the world, all producing one-of-a-kind space hardware that must come together out there in space and work perfectly the first time, its phenomenal. This is definitely outside the experience any of us ever created before."* Doug Stone, Boeing VP and ISS PM

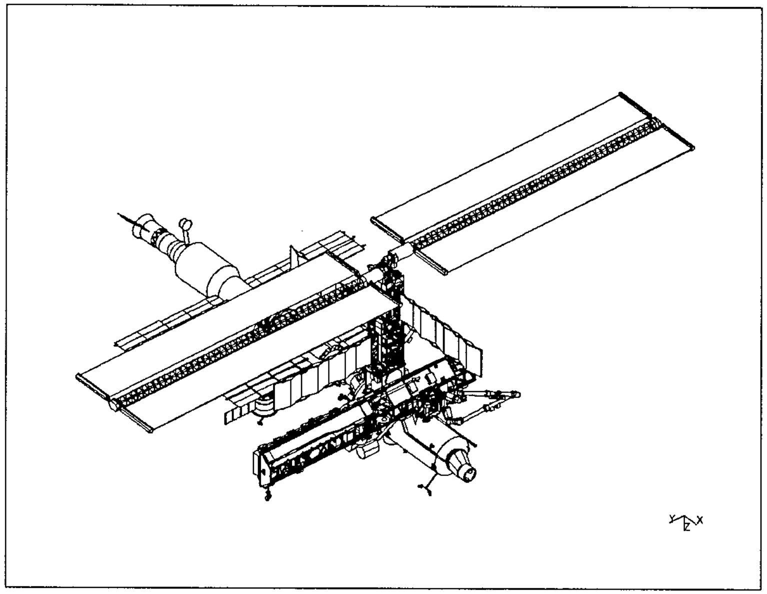
Lockheed Martin

LOCKHEED MARTIN

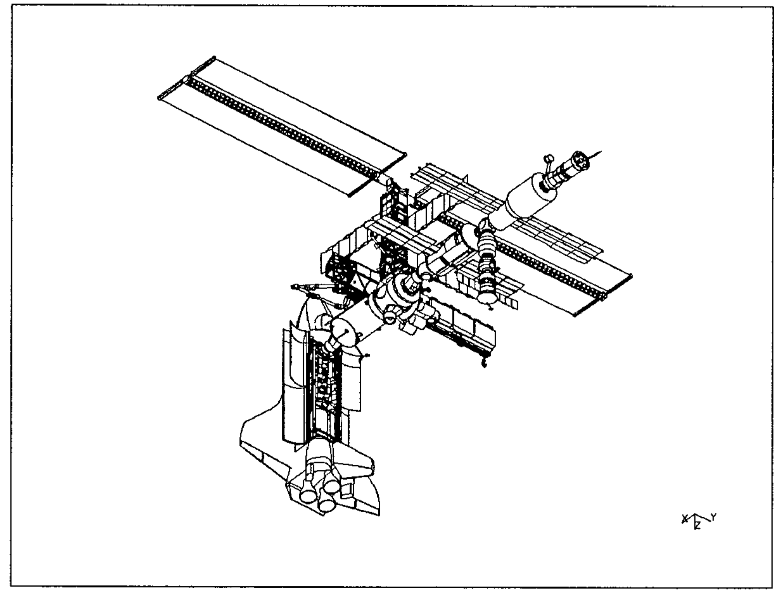
- Systems Engineering Modeling and Design Analysis Laboratory (SEMDA)
- Model all hardware elements and combine properties in order to analyze various ISS configurations
- 112 unique configurations include:
  - all free-flying stages
  - Shuttle rendezvous
  - Re-supply vehicles
  - Intermediate assembly phases
- Output includes:
  - mass properties
  - 3D and isometric drawings
  - aerodynamic properties
- Output goes to:
  - Guidance, Navigation & Control personnel

Analysis

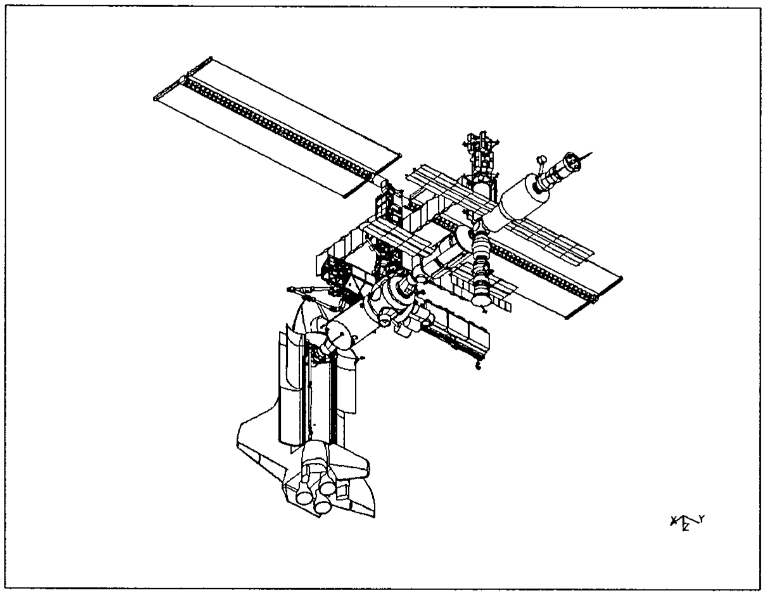
- Reproduce data from SEMDA's Design Analysis Cycle #6 from the *"International Space Station On-Orbit Assembly, Modeling, and Mass Properties Databook"*
- Calculate the mass properties from Stage 9A to Stage 9A.1-AS through the addition of the Science Power Platform (configurations 56 & 59)
- Shuttle and all its maneuvers taken out of the analysis.



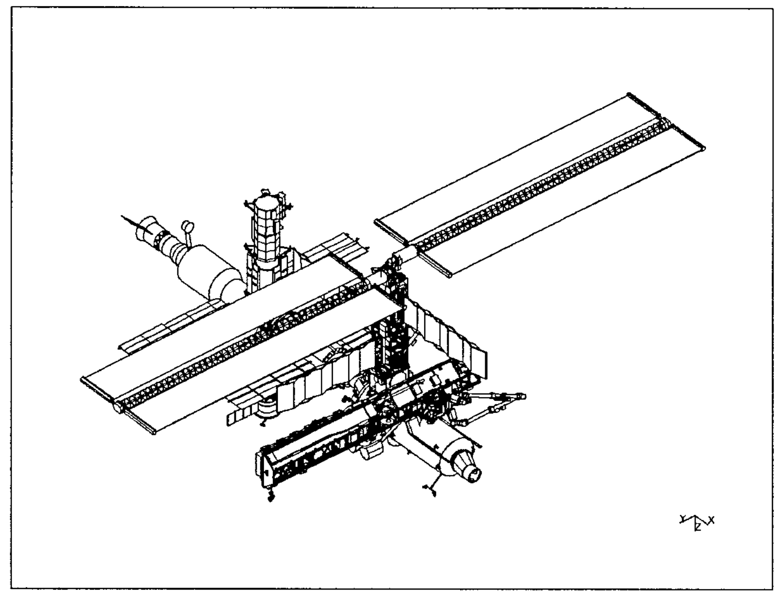
Conf 56: Stage 9A



Conf 57: Stage 9A.1+OAR



Conf 58: Stage 9A.1+OBS



Conf 59: Stage 9A.1-AS

Tools of the Trade

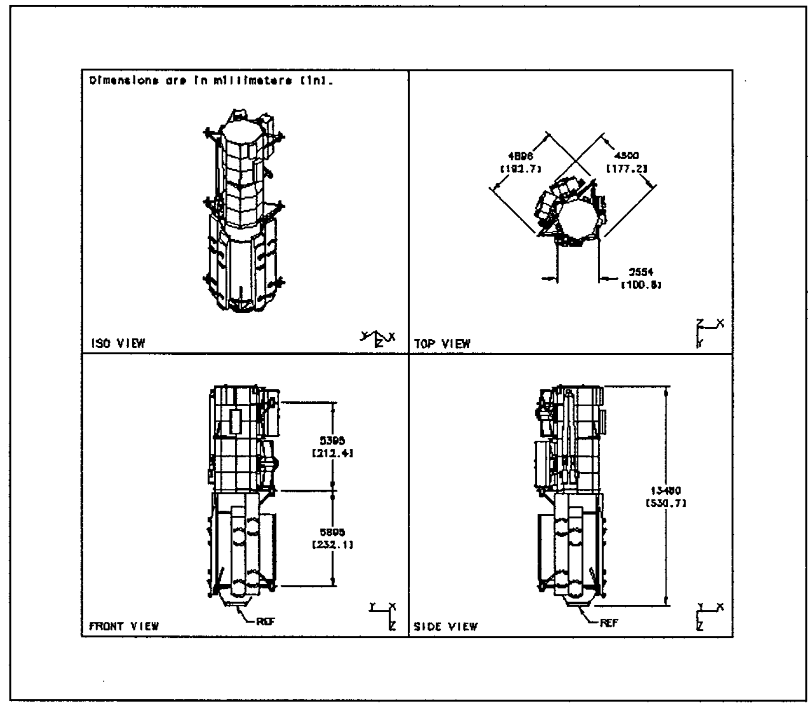
$$I_x = \int_B (y^2 + z^2)\,dm$$
$$I_y = \int_B (x^2 + z^2)\,dm$$
$$I_z = \int_B (x^2 + y^2)\,dm$$
$$I_{xy} = \int_B (xy)\,dm$$
$$I_{xz} = \int_B (xz)\,dm$$
$$I_{yz} = \int_B (yz)\,dm$$

Moments and Products of Inertia: dependant on mass and geometry
relations among angular momentum, angular velocity, rotational energy for attitude control

Principal Moments occur in principal frame with use of Euler Angles

$$\begin{bmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{xy} & I_y & -I_{yz} \\ -I_{xz} & -I_{yz} & I_z \end{bmatrix} \rightarrow \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix}$$

$$I_{SPP} = \begin{bmatrix} 237295 & 0 & 0 \\ 0 & 237295 & 0 \\ 0 & 0 & 29400 \end{bmatrix} kg \cdot m^2$$



14,700 kg, 14m x .5 m
9% increase in station mass

Assume:cylindrical, homogenous

Analysis

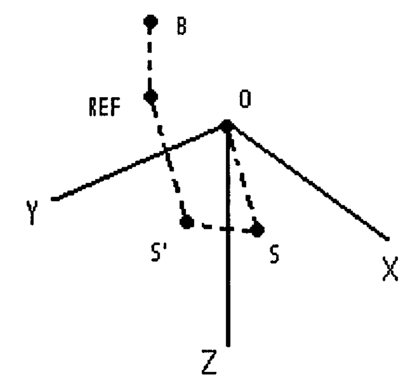
- Inertia are only compatible when measure about same point
- Parallel Axis Theorem⇒

$$I_x^* = I_x + m\left(c_y^2 + c_z^2\right)$$

$$I_{xy}^* = I_{xy} + mc_x c_y$$

$$\begin{bmatrix} 0 \\ 0 \\ -6740 \end{bmatrix}_B^{REF} mm + \begin{bmatrix} -23722 \\ 0 \\ 3015 \end{bmatrix}_{REF}^{O} mm = \begin{bmatrix} -23722 \\ 0 \\ -3725 \end{bmatrix}_B^{O} mm$$

- Not measured about ISS origin, but ISS center of mass, which just changed S⇒S’



Note to figure: O=ISS origin, REF=body origin, B=body CM., S=station CM, S’=new station CM.

Analysis

- New center of mass: $\bar{x} = \dfrac{\sum x_i m_i}{\sum m_i} = \dfrac{x_{station} m_{station} + x_{SPP} m_{SPP}}{m_{station} m_{SPP}} = -11.24m$
  - used CM from previous stage

$$\begin{bmatrix} -23.722 \\ 0 \\ -3.725 \end{bmatrix}_B^O m - \begin{bmatrix} -11.24 \\ 1.25 \\ 1.92 \end{bmatrix}_{S'}^O m = \begin{bmatrix} -12.482 \\ -1.25 \\ -5.645 \end{bmatrix}_B^{S'} m$$

- Can now do parallel axis for I_{SPP} about S':

$$I_{stage9A.1} = I_{stage9A} + I_{SciencePowerPlatform}$$

$$\begin{bmatrix} 9020468 & -2317541 & 2197558 \\ -2317541 & 33107536 & 282474 \\ 2197558 & 282474 & 32338591 \end{bmatrix} = \begin{bmatrix} 8291774 & -2088184 & 3263206 \\ -2088184 & 30111546 & 386274 \\ 3263206 & 386274 & 29995958 \end{bmatrix} + \begin{bmatrix} 728694 & -229357 & -1065648 \\ -229357 & 2995990 & -103800 \\ -1065648 & -103800 & 2342633 \end{bmatrix} kg \cdot m^2$$

Comparison

Parameter	Lockheed Martin Space Systems and Services	UCCS Masters of Engineering Student	Percent Error
Stage 9A.1 Center of Mass (m)	X_A=-12.24 Y_A=1.25 Z_A=1.93	X_A=-12.24 Y_A=1.25 Z_A=1.92	0 0 0.51
Stage 9A.1 Inertia Tensor (kg·m^2)	I_x=9,010,859 I_y=33,301,176 I_z=32,526,662 I_{xy}=2,338,366 I_{xz}=-2,152,867 I_{yz}=-274,965	I_x=9,020,468 I_y=33,107,536 I_z=32,338,591 I_{xy}=2,317,541 I_{xz}=-2,197,558 I_{yz}=-282,474	0.1 0.58 0.58 0.89 2.07 2.73
Stage 9A.1 Principal Moments of Inertia (kg·m^2)	I_1=8,591,202 I_2=33,530,140 I_3=32,717,358	I_1=8,593,000 I_2=33,335,000 I_3=32,358,000	0.02 0.58 0.55

Error due to SPP CM not in geometric center; Eigenvalue problem for Principal moments done in Matlab

Conclusion:

- The same analysis can be repeated throughout assembly or operational life cycle (solar panels)
- Computers save time, pencil lead--add flexibility
- These tools bridge the gap between what appears on paper and what happens in space

Gravity Gradient

$$T_{NET} = 3\omega_o^2 \begin{bmatrix} \phi\left(I_3 - I_2\right) \\ -\theta\left(I_1 - I_3\right) \\ -\phi\theta\left(I_2 - I_1\right) \end{bmatrix}^{NRD}$$

$$I_1\ddot{\phi} + \left(I_2 - I_3\right)\phi\omega_o^2 + \left(I_2 - I_1 - I_3\right)\omega_o\dot{\psi} = 3\omega_o^2\left(I_3 - I_2\right)\phi$$

$$I_2\ddot{\theta} = -3\omega_o^2\left(I_1 - I_3\right)\theta$$

$$I_3\ddot{\psi} + \left(I_2 - I_1\right)\omega_2^2\psi - \left(I_2 - I_1 - I_3\right)\omega_o\dot{\phi} = 0$$

- Pitch stable if: $$\frac{3\omega_o^2\left(I_{roll} - I_{yaw}\right)\theta}{I_{pitch}} > 0$$

Gravity Gradient

- Roll and Yaw are coupled:

$$K_R = \frac{(I_2 - I_3)}{I_1} \qquad K_Y = \frac{(I_2 - I_1)}{I_3}$$

- Characteristics equation:

$$s^4 + [1 + 3K_R + K_R K_Y]\omega_0^2 s^2 + 4K_Y K_R \omega_0^4 = 0$$

$$K = K_R (3 + K_Y)\omega_0^2$$

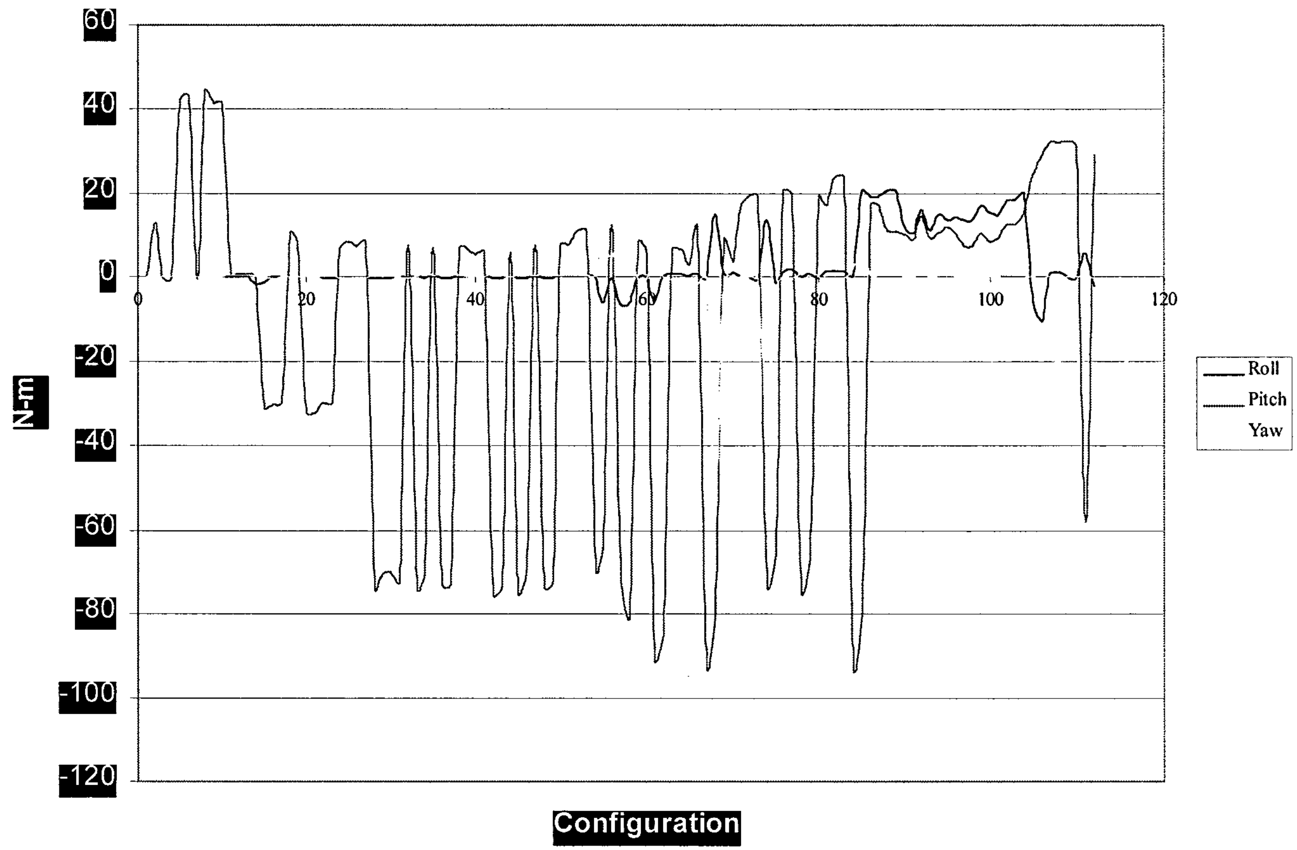
Gravity Gradient Application

- Created spreadsheet to analyze to all 112 SEMDA Lab configurations
- Entered Euler Angles and Principal Moments of Inertia
- Calculated net torque about roll, pitch, & yaw
- Classified each as Anti-symmetric ($I_1<I_2<I_3$), Axisymmetric ($I_1=I_2>I_3$) or Symmetric (within 5%)
- Stable for pitch
- Calculated K_Y, K_R, and K
- Defined stability about pitch and roll

Gravity Gradient Analysis

- Torques
- ~40 configurations were unstable for pitch
  - Orbiter attached

Small angle assumption



Gravity Gradient Analysis

- 72 Stable for Pitch
  - 24 “Always Stable”
  - 9 “Always Marginally Stable”
  - 24 “Marginally Stable for small K, then Unstable”
  - 13 “Always Unstable”

- 40 Unstable for Pitch
  - 30 “Always Stable”
  - 5 “Always Marginally Stable”
  - 0 “Marginally Stable for small K, then Unstable”
  - 6 “Always Unstable”

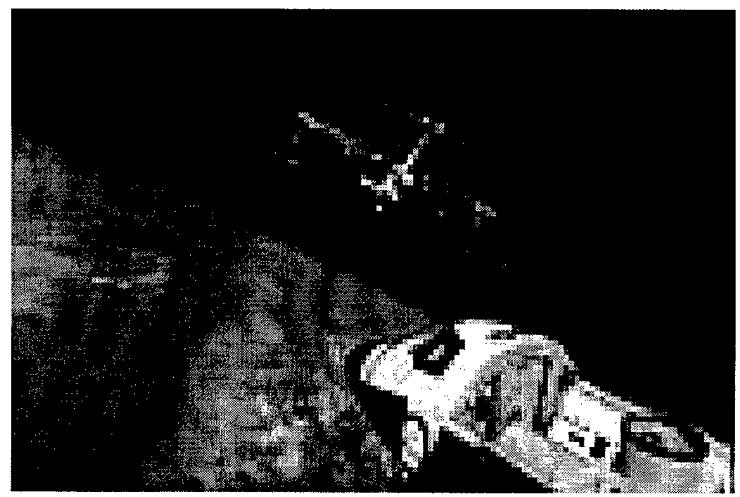
Root Locus plots

$$KF(s) = K\frac{\left(s^2 + \frac{4K_Y\omega_o^2}{3+K_Y}\right)}{s^2\left(s^2+\omega_o^2\right)} = -1$$

Effects of the Space Shuttle on ISS Dynamics

Conf	ϕ_{roll}	θ_{pitch}	ψ_{yaw}	T_{Roll}	T_{Pitch}	T_{Yaw}	Inertia Rank	Stable for Pitch?	Stability in Roll/Yaw
111 (16A+OBS)	-1.12	10.0	8.3	5.65	-58.0	0.14	$I_1<I_2<I_3$	NO	Always Unstable!
112 (16A)	0.37	-7.25	-3.26	-2.35	29.52	-0.11	$I_2<I_1<I_3$	YES	Marginally Stable for small K, then Unstable

You want me
to park this
WHERE?!?



Conclusion

- Displayed tools for dynamics of aerospace vehicles
- Applied tools to much larger project
- Analyzed a wide variety of shapes, sizes, and orientations
- ISS personnel will have their work cut out for them